من إصدارات

أكاديمية الفيزياء للتعليم الإلكتروني

Electronics Fundamentals
Circuits Devices and Applications

سلسلة محاضرات
أساسيات علم الإلكترونيات

الدكتور حازم فلاح سكيك

استاذ الفيزياء المشارك

جامعة الأزهر-غزة

أكاديمية الفيزياء

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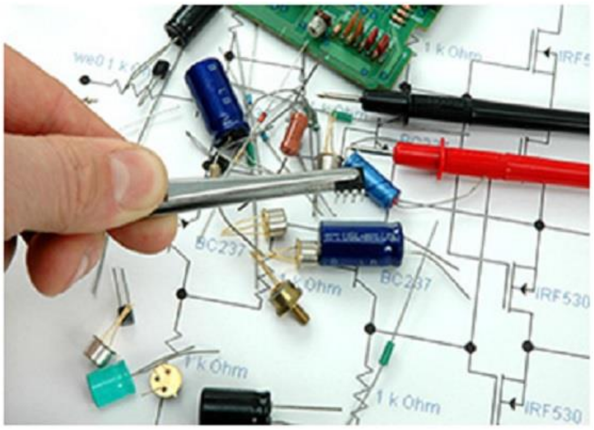
سلسلة محاضرات
اساسيات الالكترونيات
Electronics Fundamentals
Circuits Devices and Applications

إعداد وشرح
الدكتور حازم فلاح سكيك

المحتويات



مقدمة



ان التقدم الهائل في مجال عالم التقنيات التي نشـهدها في يومنا هذا أصـبحت مرتبطة بشـكل وثيق بتقدم علم الإلكترونيات - كل يوم نسمع بتطور جديد في هذا العلم وعلى سـبيل المثال نجح فريق من العلماء الأمريكيين في "مختبرات بيل" من تطوير أصـغر ترانزسـتور في العالم يسـمح تصـميمه الجديد بالاسـتمرار في تصـغير شرائح السـيلكون وقد يتمكنون من مضاعفة سرعة العمليات لبعض الشرائح..

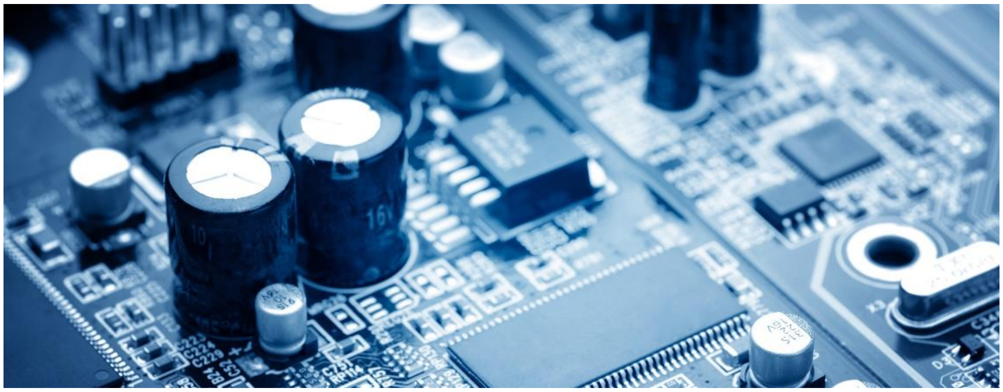
يبلغ مقاس الترانز ستور الجديد 50 نانومتر، أي ما يقل بألفي مرة عن سمك شعرة واحدة في رأس الإنسان .ويعرف الترانز ستور الجديد با سم الترانز ستور الرأسي لأن جميع مكوناته بنيت بدقة بعضها فوق بعض .ويقول أحد الباحثين إن الترانزسـتور الرأسي قد يتخطى الترانزسـتور التقليدي من حيث السرعة والأداء وجدير بالذكر أن الترانزستور التقليدي اكتشف في العام 1946.

تم بناء أول حاسب إلكتروني في العالم 1940 وبلغ وزنه 27 طناً وضم عشرات الآلاف من الصمامات وعدة كيلومترات من أسلاك النحاس وبلغت تكاليفه ملايين الدولارات بعد ذلك وباستخدام أنصاف النواقل تم اختراع الترانزسـتور الأمر الذي أدى إلى ثورة في علم الإلكترونيات وتوالت الاختراعات فتم صنع أنواع مختلفة من الترانز ستورات ثم ظهرت ثورة جديدة في علم الإلكترونيات وهي الدوائر المتكاملة حيث استطاع مجموعة من العلماء بترتيب مجموعة من العناصر الإلكترونية على شريحة صغيرة من أنصاف النواقل وكانت هذه بداية التطور الهائل الذي نراه اليوم في كل الأجهزة الإلكترونية الأمر الذي أدى إلى إنتاج صناعات ضخمة جداً وتتوالى الاختراعات في علم الإلكترونيات وما زال علم الإلكترونيات يفاجئ العام كل يوم بخبر هائل جديد.

ما هو علم الالكترونيات؟

هو علم يدور حول الأجهزة الإلكترونية ومبادئ عملها ويعتمد بشـكل أسـاسي على تدفق التيار الكهربائي في أجزائها. تشـمل الإلكترونيات على الأجهزة الالكترونية، ولفهمها وتصـميمها تلزم المعرفة بالتيار الكهربائي وأسـاسـياته والتيار المتردد والثابت .إضـافة إلى الأجزاء المكونة للأجهزة الالكترونية مثل المكثفات والمقاومات الكهربائية والثنائي دايود والترانزستور وغيرهم.

الإلكترونيات هي مجال دراسة وا ستخدام الأنظمة التي تعمل عن طريق التحكم بتدفق الالكترونات ضمنها أو حاملات الشحنة الأخرى في بعض الأوساط مثل الصمام المفرغ والمواد شبه الموصلة. وكذلك تصميم وبناء دائرة إلكترونية لحل مشاكل عملية او تصميم متطلبات تشغيل أجهزة الحاسوب وتدخل في مجال عمل كل الأجهزة التي نستخدمها في حياتنا اليومية وتعتبر دراسة علم الالكترونيات من تخصصات الفيزياء الرئيسية.



هذه السلسلة المتكاملة من محاضرات الالكترونيات موجهة لجميع الطلبة الدارسين لمقرر علم الالكترونيات وهي تركز بشكل أساسي على المفاهيم الأ سا سية لهذا العلم الوا سع حيث تغطي مفهوم المواد شبه المو صلة وو صلات الدايود وتطبيقاته المختلفة وتركز أيضا بشكل أ ساسي على الترانز ستور وانواعه وتطبيقات وتوصيه في الدوائر الالكترونية المختلفة.

آمل أن أكون قد قدمت لأبنائنا الدار سين من خلال هذا العمل المتوا ضع ما يعينهم على فهم وا ستيعاب هذا الفرع من فروع المعرفة. كما أتقدم بالشكر لكل من يقدم نصيحة حول هذه السلسلة من المحاضرات.

والله من وراء القصد

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أكاديمية الفيزياء هي عبارة عن موقع الكتروني على شبكة الانترنت يتوفر عليها المادة المساندة للمحاضرات في صورة شرح فيديو للمحاضرة مع مجموعة من الوسائل التعليمية المساعدة للطالب على فهم المادة الدراسية. تشكل الاكاديمية وسيلة تفاعلية بين المحاضر والطلبة.

موقع الأكاديمية

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نبذة عن المحاضر

د. حازم فلاح سكيك

استاذ الفيزياء المشارك بجامعة الازهر - غزة



- رئيس قسم الفيزياء بجامعة الازهر - غزة في الفترة 1993-1998
- مؤسس وعميد كلية الدراسات المتوسطة بجامعة الازهر - غزة من الفترة 1996-2005
- عميد القبول والتسجيل بجامعة الازهر - غزة في الفترتين 1998-2000 و2007-2008
- مدير الحاسب الالي بجامعة الازهر - غزة في الفترة من 1994-2000
- رئيس وحدة تكنولوجيا المعلومات بجامعة الازهر - غزة في الفترة من 2000-2005
- مؤسس شبكة الفيزياء التعليمي ومنتدى الفيزياء التعليمي.
- مؤسس أكاديمية الفيزياء للتعليم الالكتروني.
- مؤسس مركز الترجمة العلمي.
- مؤسس قناة الفيزياء التعليمي على اليوتيوب.
- رئيس تحرير مجلة الفيزياء العصرية.

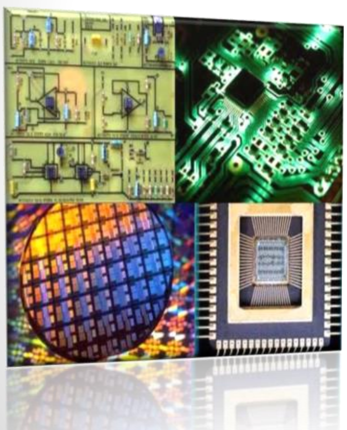
لمزيد من المعلومات يرجى زيارة

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Electronic Fundamentals

Circuits, Devices, and Applications

Lecture 0: Introduction

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What is Electronics?

Electronics, branch of physics and electrical engineering that deals with the emission, behavior, and effects of electrons and with electronic devices.

The science and technology of the conduction of electricity in a vacuum, a gas, or a semiconductor, and devices based on them.



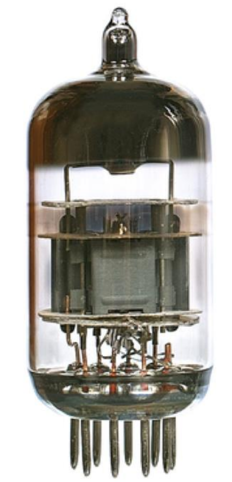
The modern discipline of electronic engineering was to a large extent born out of telephone, radio, and television-equipment development and the large amount of electronic-systems development during World War II of radar, sonar, communication systems, and advanced ammunition and weapon systems.





History of Electronics

- The history of electronics is a story of the twentieth century and three key components—the **vacuum tube**, the **transistor**, and the **integrated circuit**.
- In 1883, **Thomas Edison** discovered that electrons will flow from one metal conductor to another through a **vacuum**. This discovery of conduction became known as the Edison effect.
- In 1904, **John Fleming** applied the Edison effect in inventing a two-element **electron** tube called a **diode**. These **vacuum tubes** were the devices that made manipulation of electrical **energy** possible so it could be amplified and transmitted.

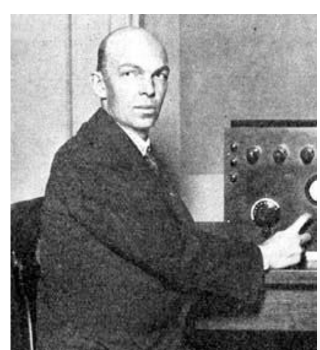


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- The first applications of electron tubes were in radio communications. **Marconi** pioneered the development of the wireless **telegraph** in 1896 and long-distance radio communication in 1901.
- In 1918, **Edwin Armstrong** invented the "super-heterodyne receiver" that could select among radio signals or stations and could receive distant signals.
- Radio broadcasting grew astronomically in the 1920s as a direct result. **Armstrong** also invented wide-band **frequency** modulation (FM) in 1935; only AM or amplitude modulation had been used from 1920 to 1935.



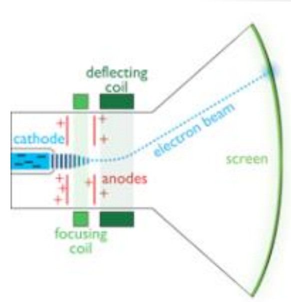
Guglielmo Marconi

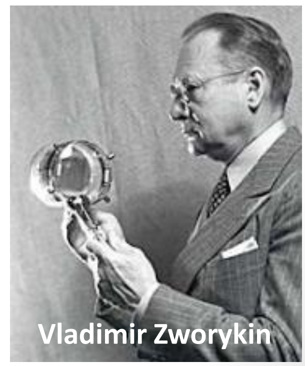


Edwin Armstrong

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- Communications technology was able to make huge advances before World War II as more specialized tubes were made for many applications. Radio as the primary form of education and entertainment was soon challenged by television, which was invented in the 1920s but didn't become widely available until 1947.
- When an electronic system was proved superior, Bell Labs engineers introduced the cathode ray picture tube and color television. But **Vladimir Zworykin**, an engineer with the Radio Corporation of America (RCA), is considered the "father of the television" because of his inventions, the picture tube and the iconoscope camera tube.




Vladimir Zworykin

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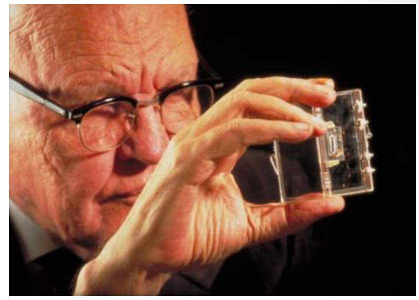
- After the war, electron tubes were used to develop the first computers, but they were impractical because of the sizes of the electronic components.
- In 1947, the transistor was invented by a team of engineers from Bell Laboratories. **John Bardeen, Walter Brattain, and William Shockley** received a Nobel prize for their creation, but few could envision how quickly and dramatically the transistor would change the world.
- The transistor functions like the vacuum tube, but it is tiny by comparison, weighs less, consumes less power, is much more reliable, and is cheaper to manufacture.


John Bardeen, Walter Brattain, and William Shockley

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- The concept of the integrated circuit was proposed in 1952 by **Geoffrey W. A. Dummer**, a British electronics expert with the Royal Radar Establishment.
- Integrated circuit combined transistors and diodes (active devices) and capacitors and resistors (passive devices) on a planar unit or chip.
- **Bipolar transistors** and **digital integrated circuits** were made first, but analog ICs, large-scale integration (LSI), and very-large-scale integration (VLSI) followed by the mid-1970s.
- VLSI consists of thousands of circuits with on-and-off switches or gates between them on a single chip. Microcomputers, medical equipment, video cameras, and communication satellites are only examples of devices made possible by integrated circuits.



Geoffrey W. A. Dummer





Electronic Course Objectives



- **To understand** the basic physical structure, principles of operation, electrical characteristics and circuit models of the most important semiconductor devices, and to be able to use this knowledge to analyze and design basic electronic application circuits.
- **To extend the understanding** of how electronic circuits and their functions fit into larger electronic systems.

Electronic Course Description



- Semiconductor devices,
- electronic circuits,
- electrical characteristics,
- principles of operation,
- circuit models of diodes,
- field-effect and bipolar transistors,
- analysis and design of basic application circuits.

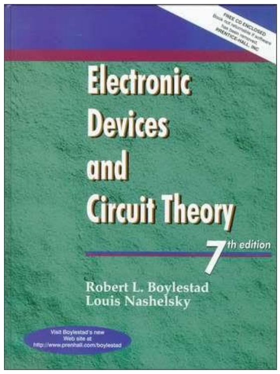
Electronic Course Outline

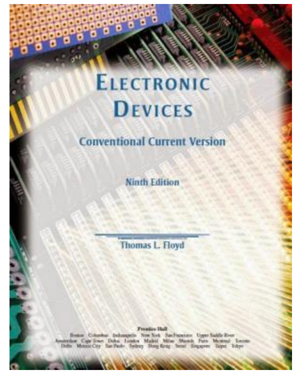
Unit 1	**Electric Circuits Essentials**	**Unit 2**	**Semiconductor Diodes**
voltages and current sources, Ohm's Law, Kirchhoff's Laws, Resistors in series and parallel, voltage and current divider circuits.		Semiconductor materials, Energy Levels, n-type and p-type extrinsic materials, Semiconductor diode, Resistance level, Diode Equivalent Circuit.	
Unit 3	**Diode Applications**	**Unit 4**	**Bipolar Junction Transistors (BJT)**
Load Line analysis, Diode Approximation, Series Diode Configurations with DC input, parallel and series-parallel configuration, Sinusoidal input: half wave rectification, Full Wave Rectification with filter		Transistor construction, transistor operation, Common-base configuration, Transistor amplifying action, Common-Emitter configuration, limits of operation.	

Electronic Course Outline

Unit 5	**DC Biasing of BJTs**	**Unit 6**	**Field-Effect Transistors (FET)**
Operating Point, Fixed Bias Circuit, Emitter Stabilizer Bias Circuit, Voltage Divider Circuit, Voltage Divider Bias, Design Operation, Transistor Switching Networks.		Construction and Characteristics of JFET, Depletion-Type MOSFET, Enhancement-Type MOSFET.	
Unit 7	**BJT Modeling**		
BJT Transistor Modeling, the Important Parameters: $Z_i i$, Z_o, A_v, A_i, the r_e Transistor Model			

Text Book



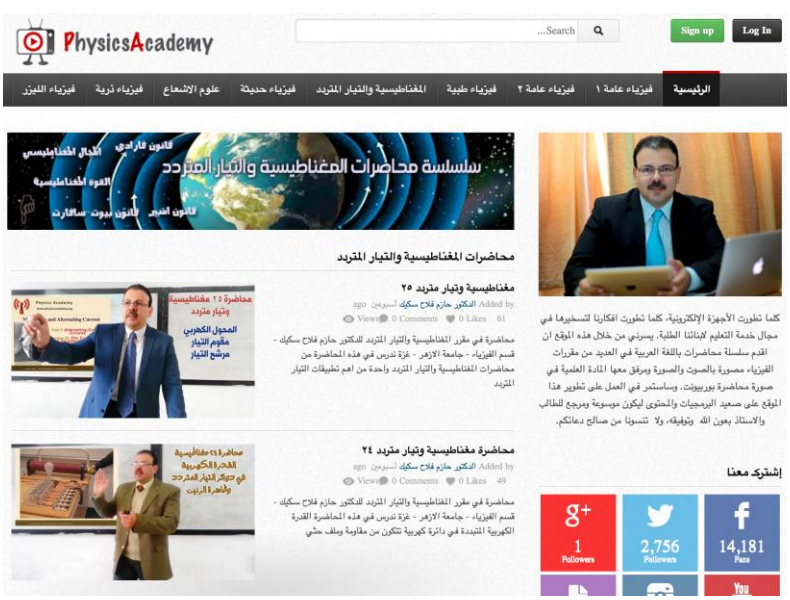


Electronic Devices and Circuit Theory
7th Edition
Robert L. Boylestad, Louis Nashelsky

Electronic Devices
9th Edition
Thomas L. Floyd

http://wps.prenhall.com/chet_floyd_electfun_8/118/30460/7797851.cw/index.html

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إلى اللقاء مع المحاضرة (١)

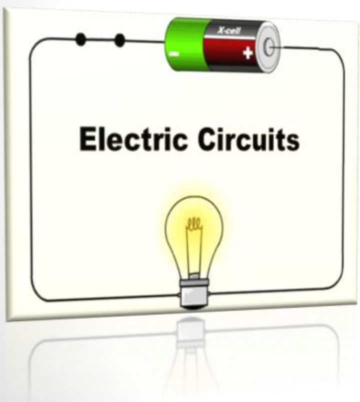
Electric Circuits Essentials

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Electronic Fundamentals

Circuits, Devices, and Applications

Lecture 1: Electric Circuits Essentials Part (1)

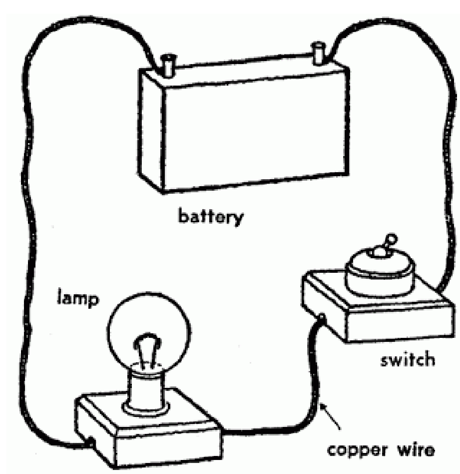
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1

Electric Circuits Essentials Part (1)

- Voltage
- Current
- Resistance
- Ohm's Law
- Energy and Power
- Series circuits



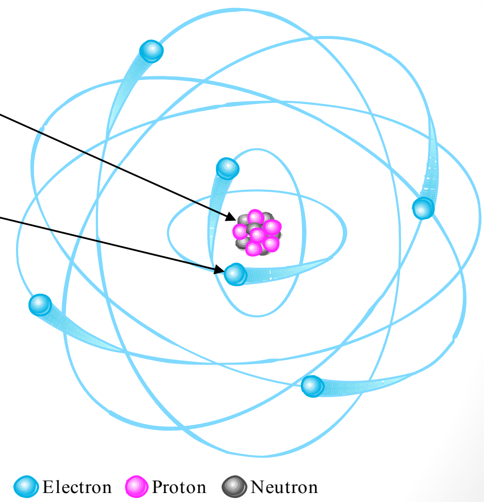
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The Bohr atom

The Bohr atom is useful for visualizing atomic structure.

- The nucleus is positively charged and has the protons and neutrons.
- Electrons are negatively charged and in discrete shells.
- The atomic number is the number of protons and determines the particular element.
- In the neutral atom, the number of electrons is equal to the number of protons.



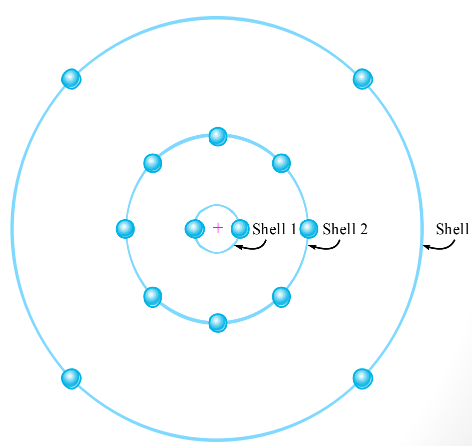
The valence shell

The outer shell is called the *valence shell*. Electrons in this shell are involved in chemical reactions and they account for electrical and thermal conductivity in metals.

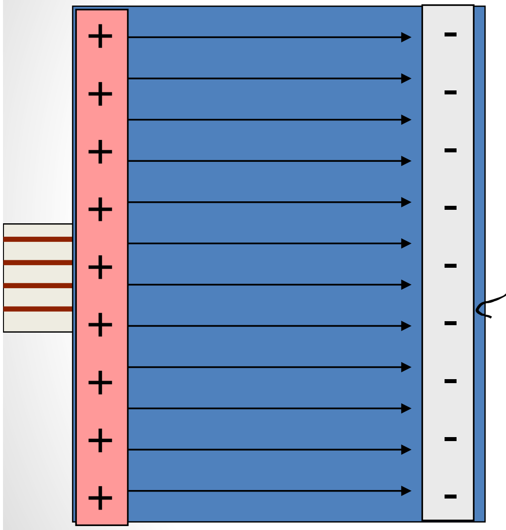
A neutral Si atom is shown. There are 4 electrons in the valence shell.

Metals have one, two or three electrons in the valence shell. The atom illustrated here is a sodium atom (Na), with only one electron in its outer shell.

Non-metals have either complete or nearly compete outer shells, so they make poor electrical conductors.



Voltage



Force is required to move a charge against the electric field.

When force is applied over a distance, work is done. Work done in moving a charge against the electric field leads to the definition of voltage:

Voltage is the work per charge done against the electric field.

$$V = \frac{W}{Q}$$ Unit of Voltage is volt

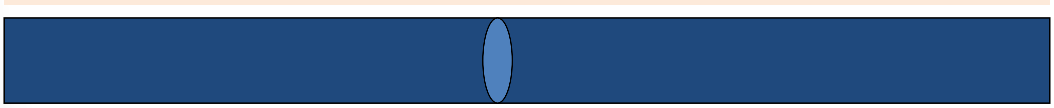
One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other.

Current

Current (*I*) is the amount of charge (*Q*) that flows past a point in a unit of time (*t*). The defining equation is:

$$I = \frac{Q}{t}$$ Unit of Current is Ampere

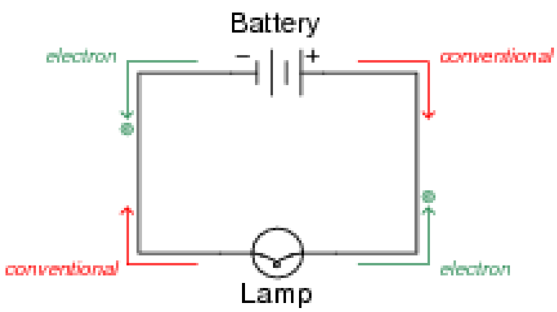
One ampere is a number of electrons having a total charge of 1 C moving through a given cross section in 1 s.



Question:

What is the current if 2 C passes a point in 5 s? 0.4 A

Conventional Current vs. Electron Flow



Conventional Flow: By convention, current flows from the positive to negative terminals.

Electron Flow: Current follows electron flow, from the negative to positive terminals.

Resistance

Resistance is the opposition to current.

One ohm (1 Ω) is the resistance if one ampere (1 A) is in a material when one volt (1 V) is applied.

Conductance is the reciprocal of resistance. $G = \frac{1}{R}$

Components designed to have a specific amount of resistance are called *resistors*.



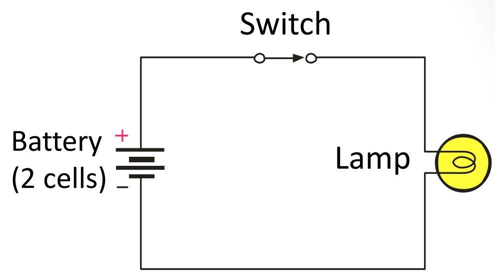
Sometimes, the resistance of wires must be accounted for. The equation for wire resistance is: $R = \frac{\rho l}{A}$

ρ = resistivity in Ω.m   *l* = length in m   *A* = cross sectional area in m^2

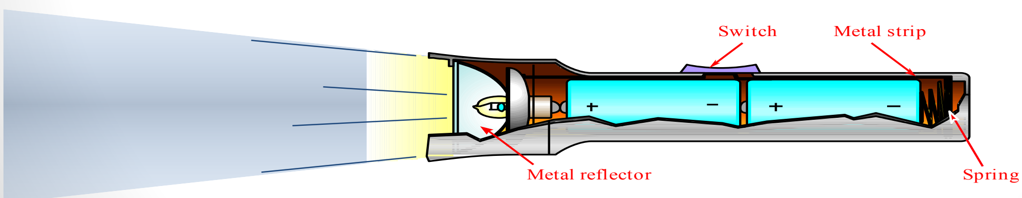
The electric circuit

A basic electric circuit consists of

1) a voltage source
2) a path
3) a load.



An example of a basic circuit is a flashlight, which has each of these plus a control element – the *switch*.



Ohm's law

The most important fundamental law in electronics is **Ohm's law**, which relates voltage, current, and resistance.

Georg Simon Ohm (1787-1854) formulated the equation that bears his name:

$$I = \frac{V}{R} \qquad V = IR \qquad R = \frac{V}{I}$$

Question:

What is the current in a circuit with a 12 V source if the resistance is 10 Ω?

1.2 A

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Example

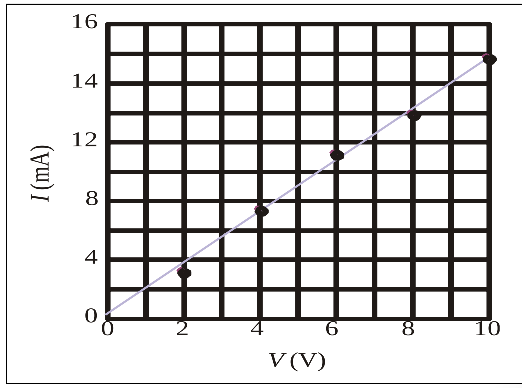
A student takes data for a resistor and fits the straight line shown to the data. **What is the conductance and the resistance of the resistor?**

The slope represents the conductance.

$$G = \frac{14.8\text{ mA} - 0\text{ mA}}{10.0\text{ V} - 0\text{ V}} = 1.48\text{ W}^{-1}$$

The reciprocal of the conductance is the resistance:

$$R = \frac{1}{G} = \frac{1}{1.48\text{ mS}} = 676\ \Omega$$

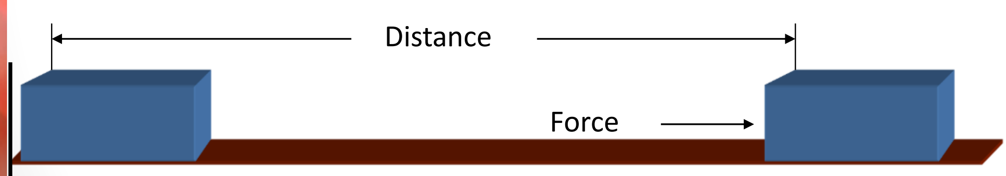


Energy and Power

When a constant force is applied to move an object over a distance, the work is the force times the distance.

The unit for work is the newton-meter (N-m) or joule (J).

Energy is closely related to work. Energy is the ability to do work. As such, it is measured in the same units as work



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Energy and Power

Power is the rate of doing work. Because it is a *rate*, a time unit is required. The unit is the joule per second (J/s), which defines a watt (W).

$$P = \frac{W}{t}$$

Example

What amount of energy is converted to heat in sliding a box along a floor for 5 meters if the force to move it is 400 N?

$W = Fd$ = (400 N)(5 m) = 2000 N-m = 2000 J

What power is developed if the box is moved in 10 s?

$$P = \frac{W}{t} = \frac{2000\ \text{J}}{10\ \text{s}} = \quad 200\ \text{W}$$

Energy and Power

In electrical work, the rate energy is dissipated can be determined from any of three forms of the power formula.

$$P = I^2R \qquad P = VI \qquad P = \frac{V^2}{R}$$

Together, the three forms are called Watt's law.

Example

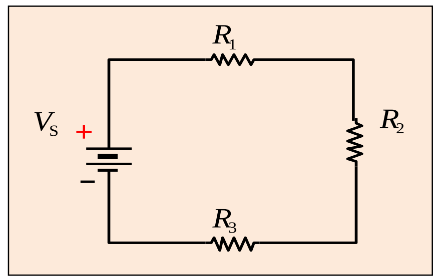
What power is dissipated in a 27 Ω resistor if the current is 0.135 A?

$$P = I^2R$$
$$= (0.135\ \text{A})^2 (27\ \text{W}) = 0.49\ \text{W}$$

Series circuits

All circuits have three common attributes. These are:

1. A source of voltage.
2. A load.
3. A complete path.

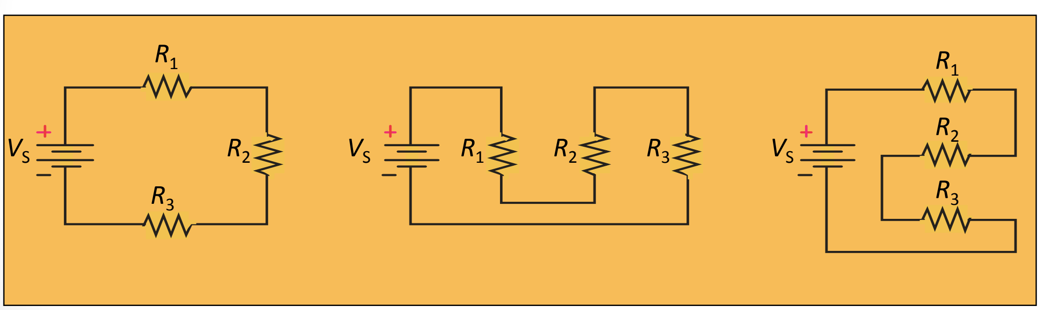


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15

Series circuits

A ***series circuit*** is one that has only one current path.



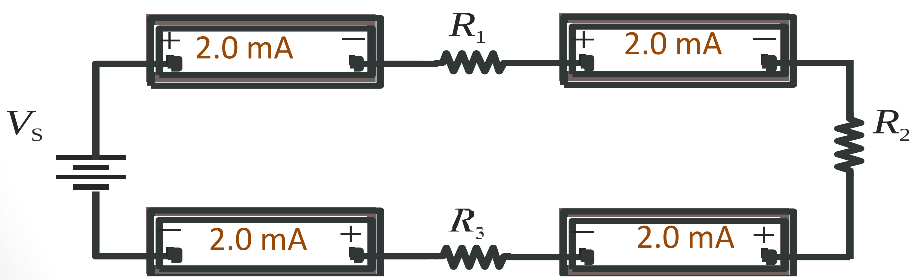
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Series circuit rule for current:

Because there is only one path, the current everywhere is the same.

For example, the reading on the first ammeter is 2.0 mA, What do the other meters read?

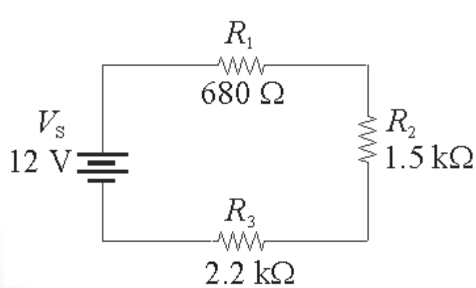


Series circuits

The total resistance of resistors in series is

the sum of the individual resistors.

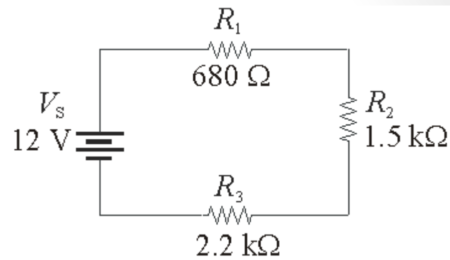
For example, the resistors in a series circuit are 680 Ω, 1.5 kΩ, and 2.2 kΩ. What is the total resistance?



4.38 kΩ

Series circuits

Tabulating current, resistance, voltage and power is a useful way to summarize parameters in a series circuit.

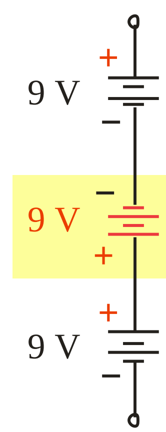


Continuing with the previous example, complete the parameters listed in the Table.

I_1= 2.74 mA	R_1= 0.68 kΩ	V_1= 1.86 V	P_1= 5.1 mW
I_2= 2.74 mA	R_2= 1.50 kΩ	V_2= 4.11 V	P_2= 11.3 mW
I_3= 2.74 mA	R_3= 2.20 kΩ	V_3= 6.03 V	P_3= 16.5 mW
I_T= 2.74 mA	R_T= 4.38 kΩ	V_S= 12 V	P_T= 32.9 mW

Voltage sources in series

Voltage sources in series add algebraically. For example, the total voltage of the sources shown is 27 V



What is the total voltage if one battery is accidentally reversed? 9 V

Kirchhoff's voltage law

Kirchhoff's voltage law is generally stated as:

The sum of all the voltage drops around a single closed path in a circuit is equal to the total source voltage in that closed path.

Kirchhoff's voltage law applies to all circuits, but you must apply it to only one closed path. In a series circuit, this is the entire circuit.

$$\sum_{i=1}^{n} V_i = 0$$

Voltage divider rule

The voltage drop across any given resistor in a series circuit is equal to the ratio of that resistor to the total resistance, multiplied by source voltage.

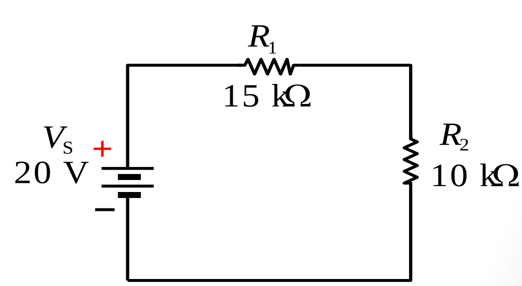
Example

What is the voltage across R_2?

The total resistance is 25 kΩ.

Applying the voltage divider formula:

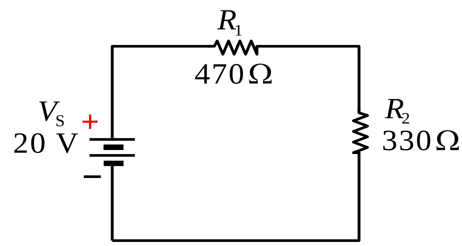
$$V_2 = \left(\frac{R_2}{R_T}\right)V_S = \left(\frac{10\ \text{k}\Omega}{25\ \text{k}\Omega}\right)20\ \text{V} = 8.0\ \text{V}$$



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Power in Series Circuits

Use the voltage divider rule to find V_1 and V_2. Then find the power in R_1 and R_2 and P_T.



Applying the voltage divider rule:

$$V_1 = \left(\frac{470\ \Omega}{800\ \Omega}\right) 20\ \text{V} = 11.75\ \text{V}$$

$$V_2 = \left(\frac{330\ \Omega}{800\ \Omega}\right) 20\ \text{V} = 8.25\ \text{V}$$

The power dissipated by each resistor is:

$$P_1 = \frac{(11.75\ \text{V})^2}{470\ \Omega} = 0.29\ \text{W}$$

$$P_2 = \frac{(8.25\ \text{V})^2}{330\ \Omega} = 0.21\ \text{W}$$

$P_T = 0.5$ W

Quiz

If the voltage in a resistive circuit is doubled, the power will be

a. halved
b. unchanged
c. doubled
d. quadrupled

d. quadrupled

The approximate power dissipated by a 330 Ω resistor with 9 V across it is

a. ¼ W
b. ½ W
c. 1 W
d. 2 W

a. ¼ W

Quiz

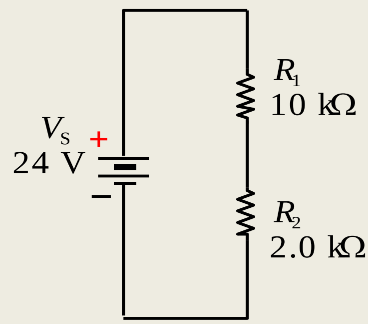
The current in the 10 kΩ resistor is

a. 0.5 mA

b. 2.0 mA

c. 2.4 mA

d. 10 mA



b. 2.0 mA

Quiz

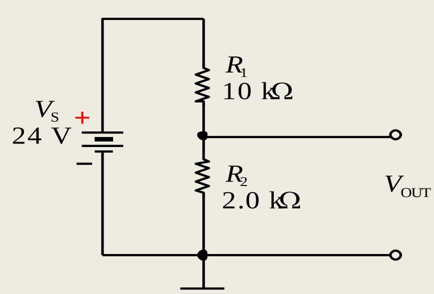
The output voltage from the voltage divider is

a. 2.0 V

b. 4.0 V

c. 12 V

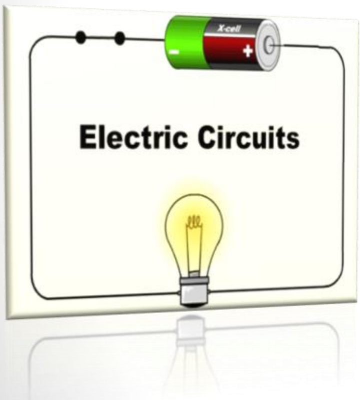
d. 20 V



b. 4.0 V

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Electronic Fundamentals

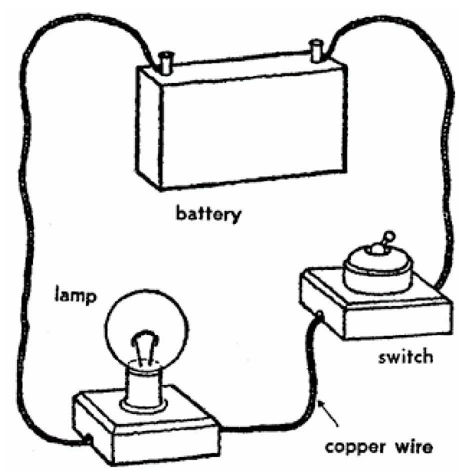
Circuits, Devices, and Applications

Lecture 2: Electric Circuits Essentials Part (2)

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Electric Circuits Essentials Part (2)

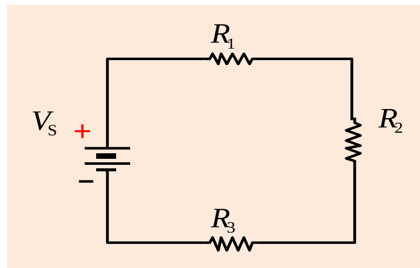
- Voltage
- Current
- Resistance
- Ohm's Law
- Energy and Power
- Series circuits



Series circuits

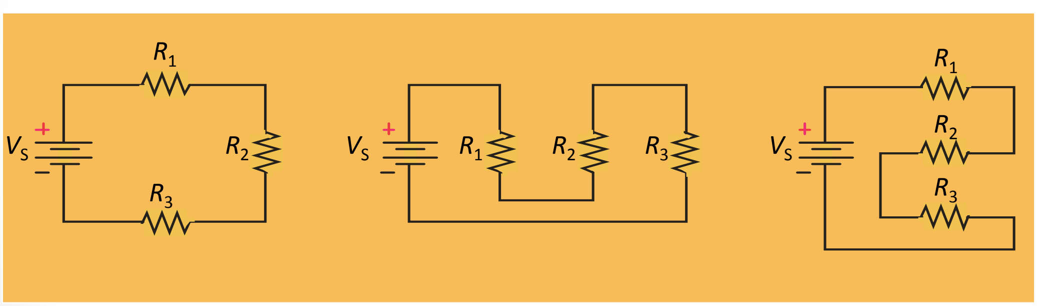
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1. A source of voltage.
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Series circuits

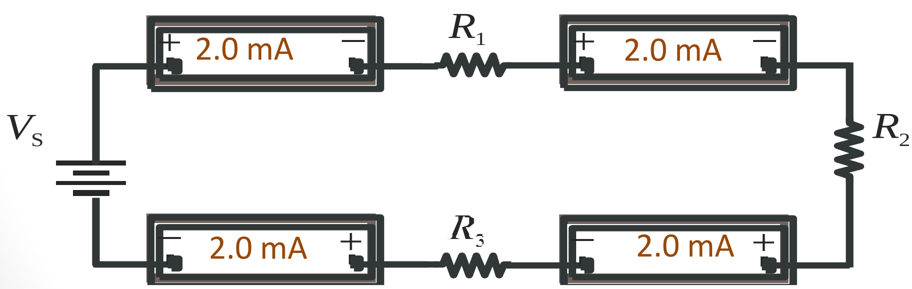
A ***series circuit*** is one that has only one current path.



Series circuit rule for current:

Because there is only one path, the current everywhere is the same.

For example, the reading on the first ammeter is 2.0 mA, What do the other meters read?



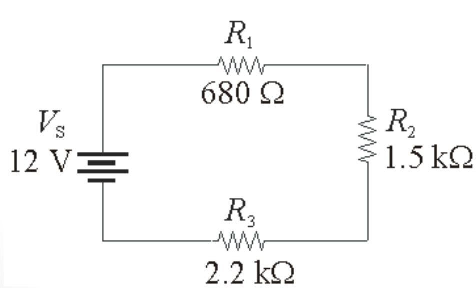
5

Series circuits

The total resistance of resistors in series is

the sum of the individual resistors.

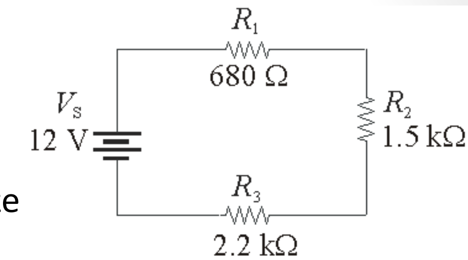
For example, the resistors in a series circuit are 680 Ω, 1.5 kΩ, and 2.2 kΩ. What is the total resistance?



4.38 kΩ

6

Series circuits



Tabulating current, resistance, voltage and power is a useful way to summarize parameters in a series circuit.

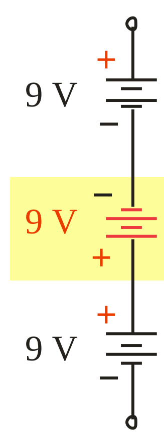
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I_2= 2.74 mA	R_2= 1.50 kΩ	V_2= 4.11 V	P_2= 11.3 mW
I_3= 2.74 mA	R_3= 2.20 kΩ	V_3= 6.03 V	P_3= 16.5 mW
I_T= 2.74 mA	R_T= 4.38 kΩ	V_S= 12 V	P_T= 32.9 mW

Voltage sources in series

Voltage sources in series add algebraically. For example, the total voltage of the sources shown is

27 V



What is the total voltage if one battery is accidentally reversed?

9 V

Kirchhoff's voltage law

Kirchhoff's voltage law is generally stated as:

The sum of all the voltage drops around a single closed path in a circuit is equal to the total source voltage in that closed path.

Kirchhoff's voltage law applies to all circuits, but you must apply it to only one closed path. In a series circuit, this is the entire circuit.

$$\sum_{i=1}^{n} V_i = 0$$

Voltage divider rule

The voltage drop across any given resistor in a series circuit is equal to the ratio of that resistor to the total resistance, multiplied by source voltage.

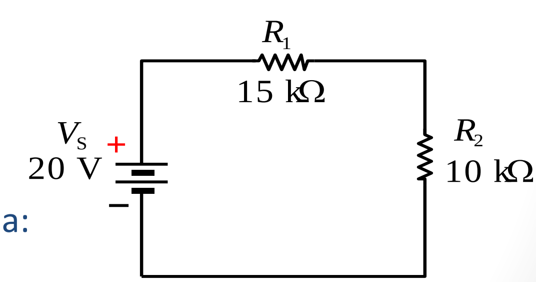
Example

What is the voltage across R_2?

The total resistance (R_T) is 25 kΩ.

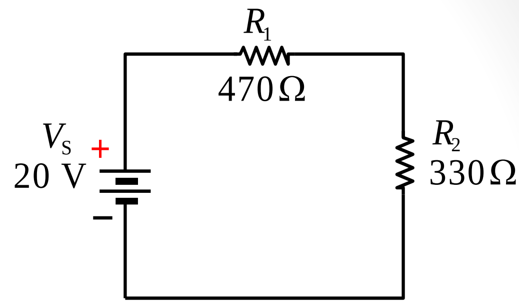
Applying the voltage divider formula:

$$V_2 = \left(\frac{R_2}{R_T}\right)V_S = \left(\frac{10\ \text{k}\Omega}{25\ \text{k}\Omega}\right)20\ \text{V} = \mathbf{8.0\ V}$$



Power in Series Circuits

Use the voltage divider rule to find V_1 and V_2. Then find the power in R_1 and R_2 and P_T.



Applying the voltage divider rule:

$$V_1 = \left(\frac{470\ \Omega}{800\ \Omega}\right)20\ \text{V} = \mathbf{11.75\ V}$$

$$V_2 = \left(\frac{330\ \Omega}{800\ \Omega}\right)20\ \text{V} = \mathbf{8.25\ V}$$

The power dissipated by each resistor is:

$$P_1 = \frac{(11.75\ \text{V})^2}{470\ \Omega} = \mathbf{0.29\ W}$$

$$P_2 = \frac{(8.25\ \text{V})^2}{330\ \Omega} = \mathbf{0.21\ W}$$

$\mathbf{P_T = 0.5\ W}$

Quiz

If the voltage in a resistive circuit is doubled, the power will be

a. halved
b. unchanged
c. doubled
d. quadrupled

d. quadrupled

The approximate power dissipated by a 330 Ω resistor with 9 V across it is

a. 0.25 W
b. 0.5 W
c. 1 W
d. 2 W

a. 0.25 W

Quiz

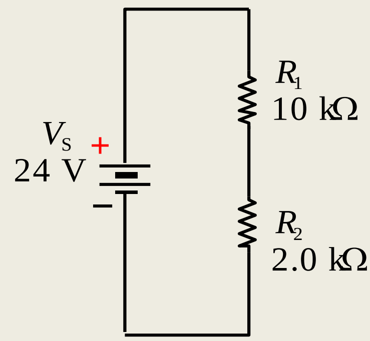
The current in the 10 kΩ resistor is

a. 0.5 mA

b. 2.0 mA

c. 2.4 mA

d. 10 mA



b. 2.0 mA

Quiz

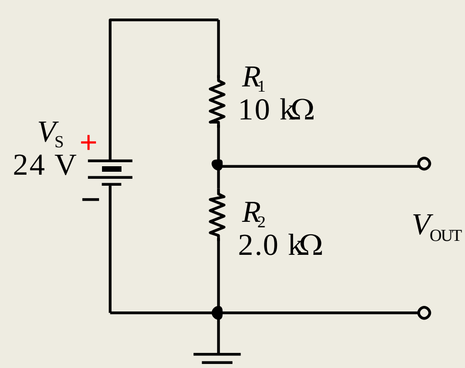
The output voltage from the voltage divider is

a. 2.0 V

b. 4.0 V

c. 12 V

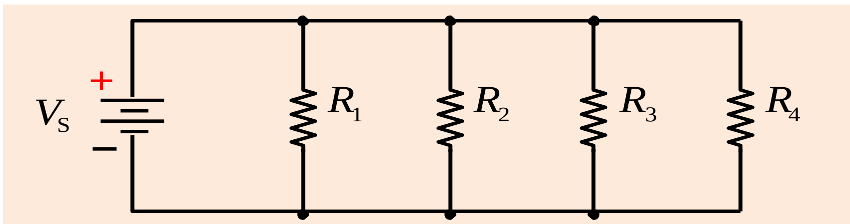
d. 20 V



b. 4.0 V

Resistors in parallel

Resistors that are connected to the same two points are said to be in parallel.



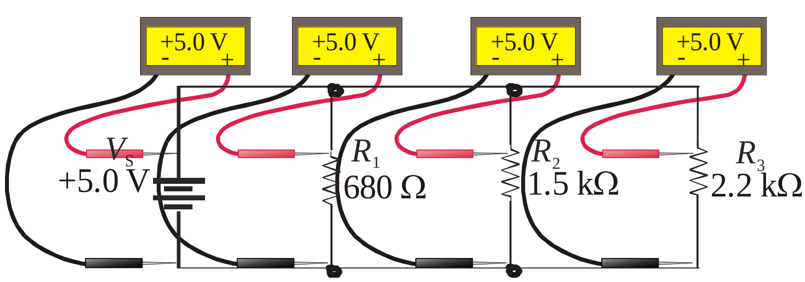
Parallel circuits

A ***parallel circuit*** is identified by the fact that it has more than one current path (branch) connected to a common voltage source.

Parallel circuit rule for voltage

Because all components are connected across the same voltage source, the voltage across each is the same.

For example, the source voltage is 5.0 V. What will a voltmeter read if it is placed across each of the resistors?

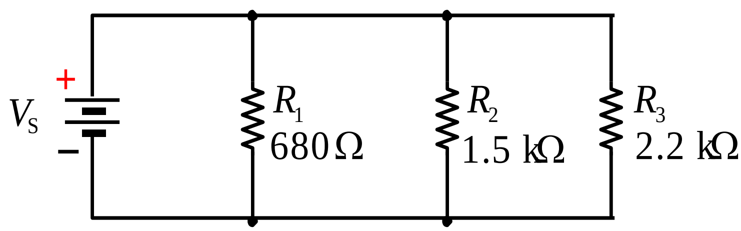


Parallel circuit rule for resistance

The total resistance of resistors in parallel is

the reciprocal of the sum of the reciprocals of the individual resistors.

For example, the resistors in a parallel circuit are 680 Ω, 1.5 kΩ, and 2.2 kΩ. What is the total resistance? **386 Ω**



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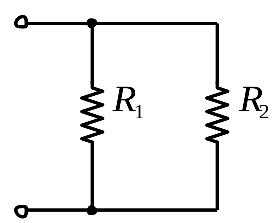
17

Special case for resistance of two parallel resistors

The resistance of two parallel resistors can be found by

either:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} \quad \text{or} \quad R_T = \frac{R_1 R_2}{R_1 + R_2}$$



Question:

What is the total resistance if R_1 = 27 kΩ and R_2 = 56 kΩ?

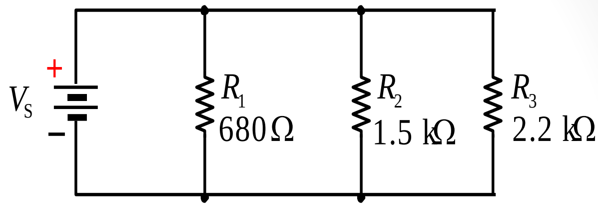
18.2 kΩ

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Parallel circuit

Tabulating current, resistance, voltage and power is a useful way to summarize parameters in a parallel circuit.



Continuing with the previous example, complete the parameters listed in the Table.

I_1= 7.4 mA	R_1= 0.68 kΩ	V_1=5.0 V	P_1= 36.8 mW
I_2= 3.3 mA	R_2= 1.50 kΩ	V_2=5.0 V	P_2= 16.7 mW
I_3= 2.3 mA	R_3= 2.20 kΩ	V_3=5.0 V	P_3= 11.4 mW
I_T= 13.0 mA	R_T= 386 Ω	V_S= 5.0 V	P_T= 64.8 mW

Kirchhoff's current law

Kirchhoff's current law (KCL) is generally stated as:

The sum of the currents entering a node is equal to the sum of the currents leaving the node.

Notice in the previous example that the current from the source is equal to the sum of the branch currents.

I_1= 7.4 mA	R_1= 0.68 kΩ	V_1=5.0 V	P_1= 36.8 mW
I_2= 3.3 mA	R_2= 1.50 kΩ	V_2=5.0 V	P_2= 16.7 mW
I_3= 2.3 mA	R_3= 2.20 kΩ	V_3=5.0 V	P_3= 11.4 mW
I_T= 13.0 mA	R_T= 386 Ω	V_S= 5.0 V	P_T= 64.8 mW

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Current divider

When current enters a node (junction) it divides into currents with values that are inversely proportional to the resistance values.

The most widely used formula for the current divider is the two-resistor equation. For resistors R_1 and R_2,

$$I_1 = \left(\frac{R_2}{R_1 + R_2}\right) I_T \quad \text{and} \quad I_2 = \left(\frac{R_1}{R_1 + R_2}\right) I_T$$

Notice the subscripts. The resistor in the numerator is not the same as the one for which current is found.

Current divider

Example

Assume that R_1 is a 2.2 kΩ resistor that is in parallel with R_2, which is 4.7 kΩ. If the total current into the resistors is 8.0 mA, what is the current in each resistor?

Solution

$$I_1 = \left(\frac{R_2}{R_1 + R_2}\right) I_T = \left(\frac{4.7\ \text{k}\Omega}{6.9\ \text{k}\Omega}\right) 8.0\ \text{mA} = \mathbf{5.45\ mA}$$

$$I_2 = \left(\frac{R_1}{R_1 + R_2}\right) I_T = \left(\frac{2.2\ \text{k}\Omega}{6.9\ \text{k}\Omega}\right) 8.0\ \text{mA} = \mathbf{2.55\ mA}$$

Notice that the *larger* resistor has the *smaller* current.

Power in parallel circuits

Power in each resistor can be calculated with any of the standard power formulas. Most of the time, the voltage is known, so the equation $P = \frac{V^2}{R}$ is most convenient.

As in the series case, the total power is the sum of the powers dissipated in each resistor.

Question:

What is the total power if 10 V is applied to the parallel combination of R_1 = 270 Ω and R_2 = 150 Ω? **1.04 W**

Question:

Assume there are 8 resistive wires that form a rear window defroster for an automobile.

(a) If the defroster dissipates 90 W when connected to a 12.6 V source, what power is dissipated by each resistive wire?

(b) What is the total resistance of the defroster?

Answer:

(a) Each of the 8 wires will dissipate 1/8 of the total power or

$$\frac{90 \text{ W}}{8 \text{ wires}} = 11.25 \text{ W}$$

(b) The total resistance is $R = \frac{V^2}{P} = \frac{(12.6 \text{ V})^2}{90 \text{ W}} = 1.76\ \Omega$

Quiz

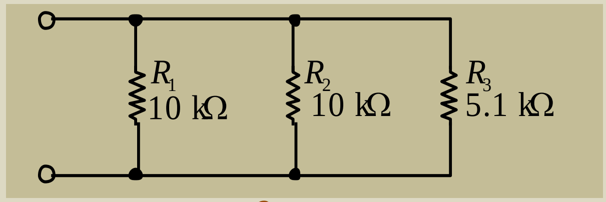
The total resistance of the parallel resistors is

a. 2.52 kΩ

b. 3.35 kΩ

c. 5.1 kΩ

d. 25.1 kΩ



3. a

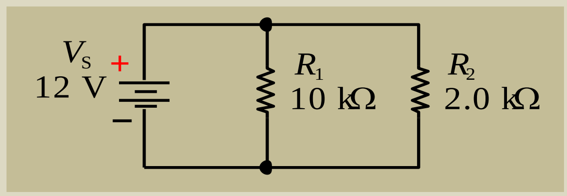
The total current leaving the source is

a. 1.0 mA

b. 1.2 mA

c. 6.0 mA

d. 7.2 mA



7. d

Quiz

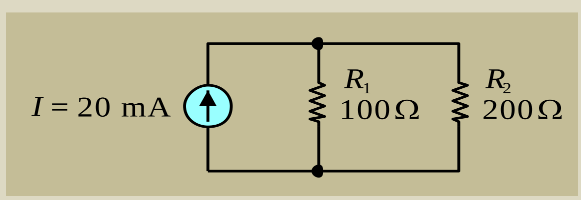
The current in R_1 is

a. 6.7 mA

b. 13.3 mA

c. 20 mA

d. 26.7 mA



8. b

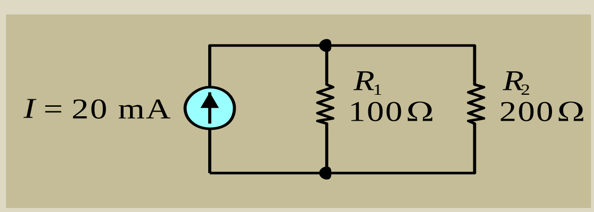
The voltage across R_2 is

a. 0 V

b. 0.67 V

c. 1.33 V

d. 4.0 V



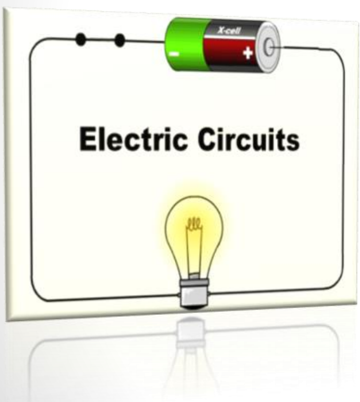
9. c

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Electronic Fundamentals

Circuits, Devices, and Applications



Lecture 3: Electric Circuits Essentials Part (3)

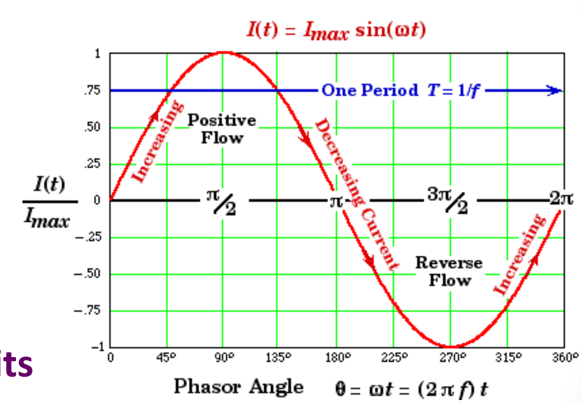
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1

Electric Circuits Essentials Part (3)

- Period and Frequency
- Generation of a sine wave
- Sine wave voltage and current values
- Phasors
- Power in resistive AC circuits



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2

A wave is a disturbance. Unlike water waves, electrical waves cannot be seen directly but they have similar characteristics. All periodic waves can be constructed from **sine waves**, which is why sine waves are fundamental.

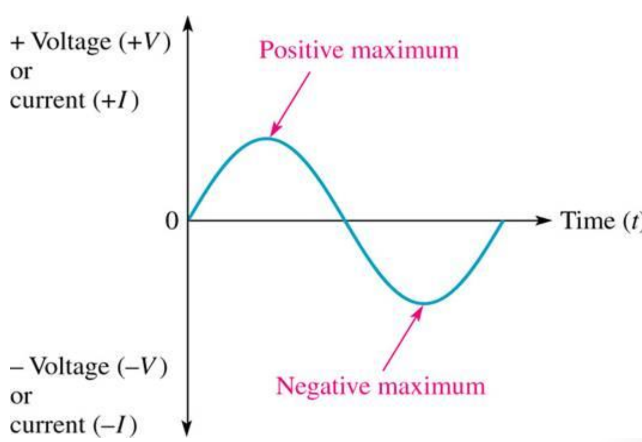


3

Sine waves

The **sinusoidal waveform** (sine wave) is the fundamental alternating current (ac) and alternating voltage waveform.

Electrical sine waves are named from the mathematical function with the same shape.



4

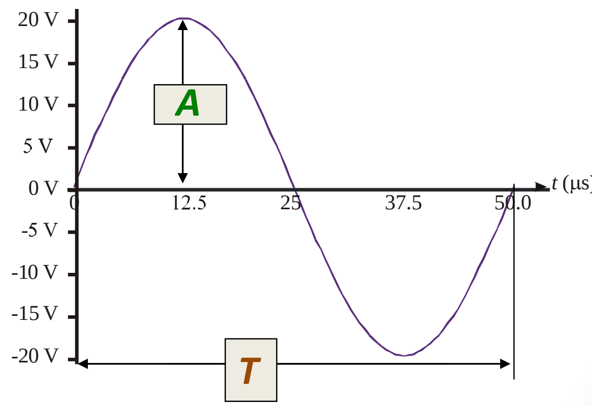
Sine waves

Sine waves are characterized by the amplitude and period. The **amplitude** is the maximum value of a voltage or current; the **period** is the time interval for one complete cycle.

Example

The amplitude (*A*) of this sine wave is 20 V

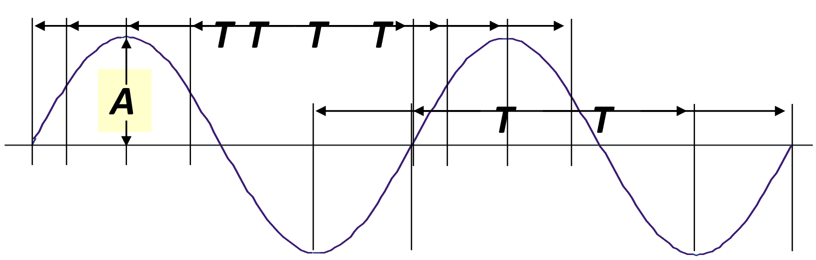
The period is 50.0 μs



5

Sine waves

The **period** of a sine wave can be measured between any two corresponding points on the waveform.



By contrast, the **amplitude** of a sine wave is only measured from the center to the maximum point.

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Frequency

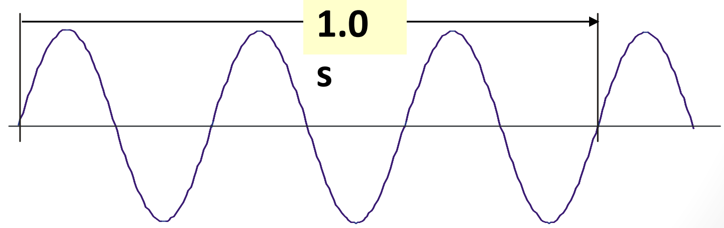
Frequency (f) is the number of cycles that a sine wave completes in one second.

Frequency is measured in **hertz** (Hz).

Example

If 3 cycles of a wave occur in one second, the frequency is

3.0 Hz



Period and frequency

The period and frequency are reciprocals of each other.

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

Thus, if you know one, you can easily find the other.

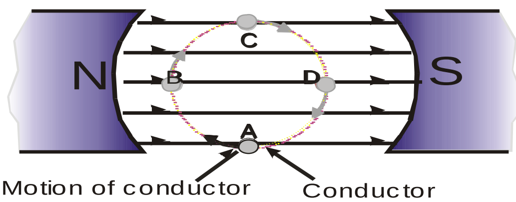
Example

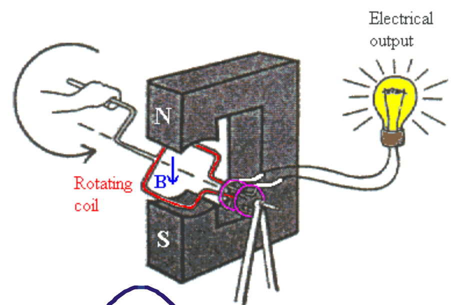
If the period is 50 μs, the frequency is 20,000 Hz = 20 kHz.

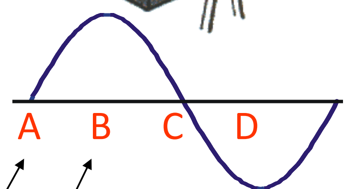
Generation of a sine wave

Sinusoidal voltages are produced by ac generators and electronic oscillators.

When a conductor rotates in a constant magnetic field, a sinusoidal wave is generated.

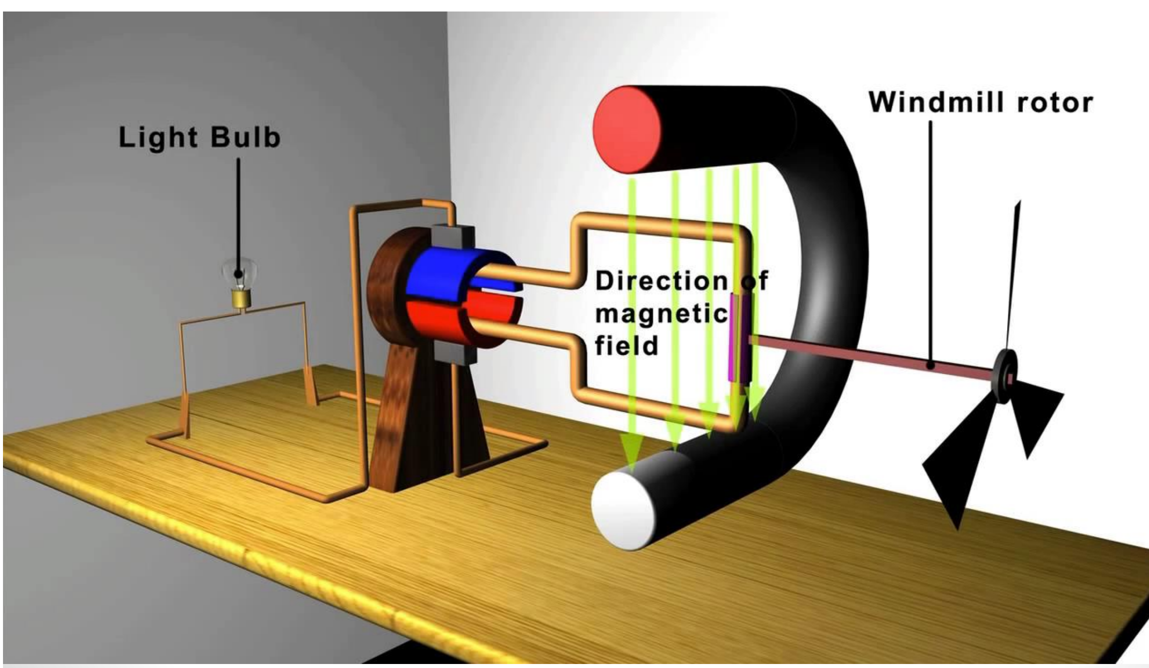






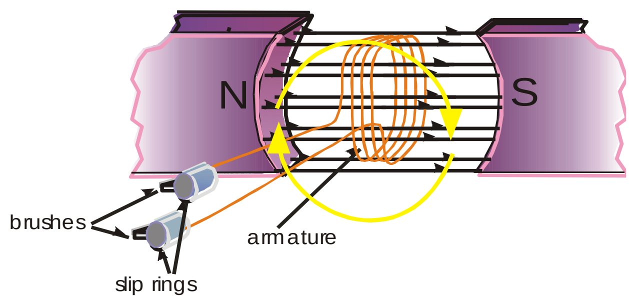
When the conductor is moving parallel with the lines of flux, no voltage is induced.

When the loop is moving perpendicular to the lines of flux, the maximum voltage is induced.



AC generator

Generators convert rotational energy to electrical energy. A stationary field alternator with a rotating coil is shown. The coil has an induced voltage, which is connected through slip rings and brushes to a load.



Function generators

Typical controls:

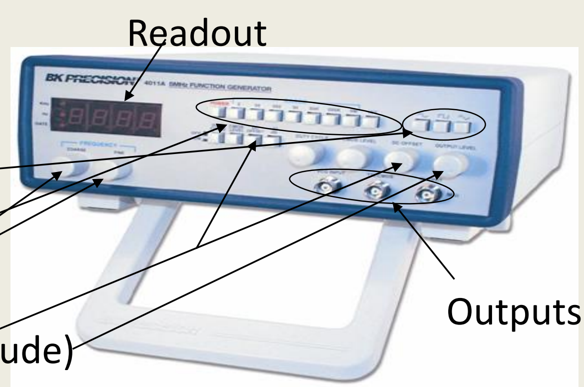
Function selection

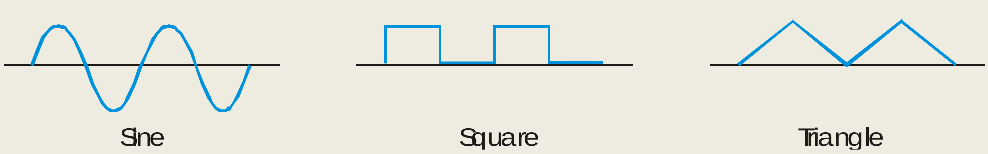
Frequency Range

Adjust

Output level (amplitude)

DC offset



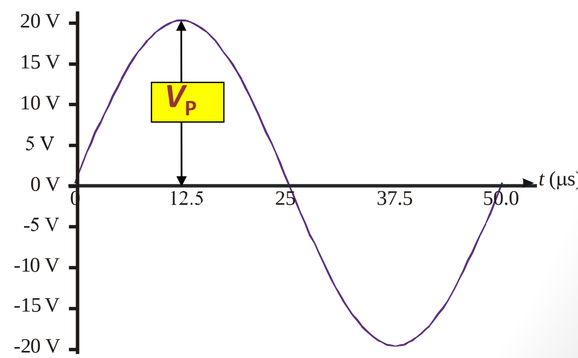


Sine wave voltage and current values

There are several ways to specify the voltage of a sinusoidal voltage waveform. The amplitude of a sine wave is also called the **peak value**, abbreviated as V_P for a voltage waveform.

Example

The peak voltage of this waveform is **20 V.**



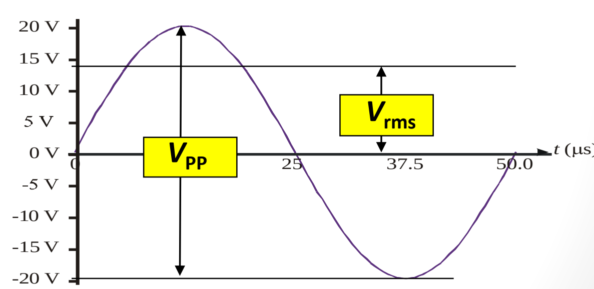
Sine wave voltage and current values

The voltage of a sine wave can also be specified as either the peak-to-peak or the rms value. The **peak-to-peak** is twice the peak value. The **rms value** is 0.707 times the peak value.

Example

The peak-to-peak voltage is 40 V.

The rms voltage is 14.1 V.



Sine wave equation

Instantaneous values of a wave are shown as v or i. The equation for the instantaneous voltage (v) of a sine wave is

$$v = V_p \sin\theta$$

where

V_p = Peak voltage

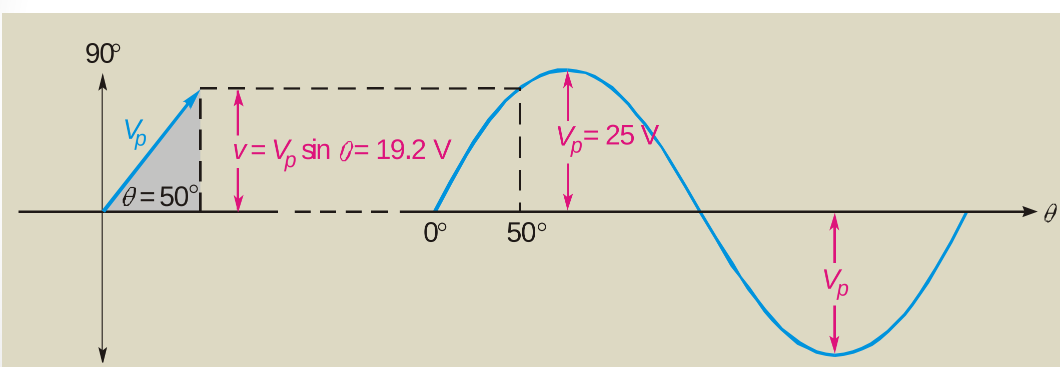
θ = Angle in rad or degrees

Example

If the peak voltage is 25 V, the instantaneous voltage at 50 degrees is **19.2 V**

Sine wave equation

A plot of the example in the previous slide (peak at 25 V) is shown. The instantaneous voltage at 50° is 19.2 V as previously calculated.

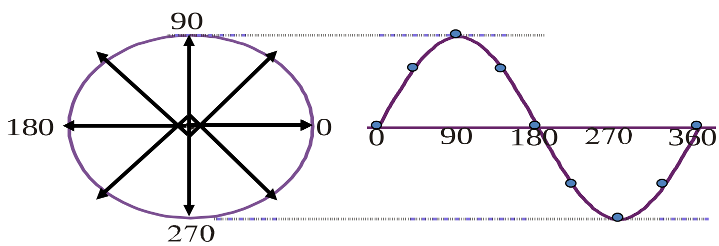


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Phasors

The **sine wave** can be represented as the projection of a vector rotating at a constant rate. This rotating vector is called a **phasor**.

Phasors are useful for showing the phase relationships in ac circuits.



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Phase shift

The phase of a sine wave is an angular measurement that specifies the position of a sine wave relative to a reference. To show that a sine wave is shifted to the left or right of this reference, a term is added to the equation given previously.

$$v = V_P \sin(\theta \pm \phi)$$

where

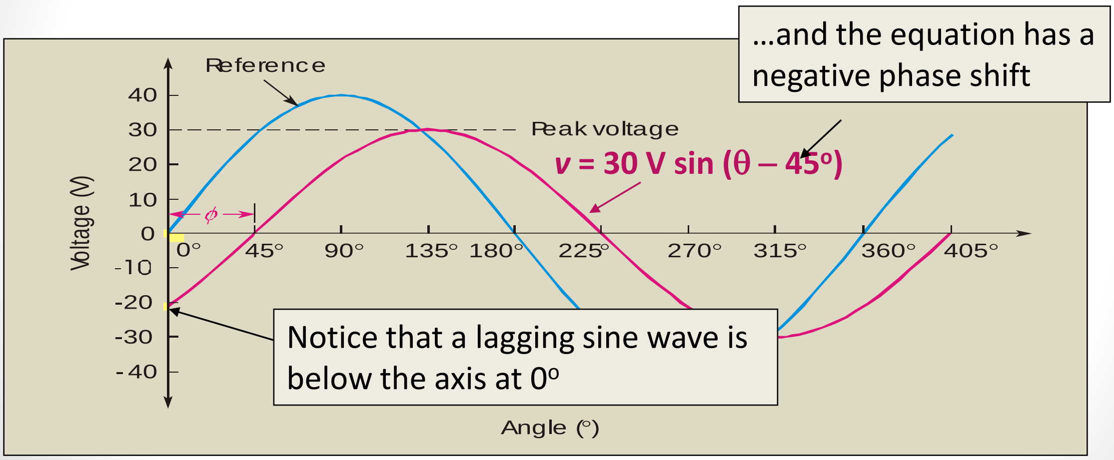
ϕ = Phase shift

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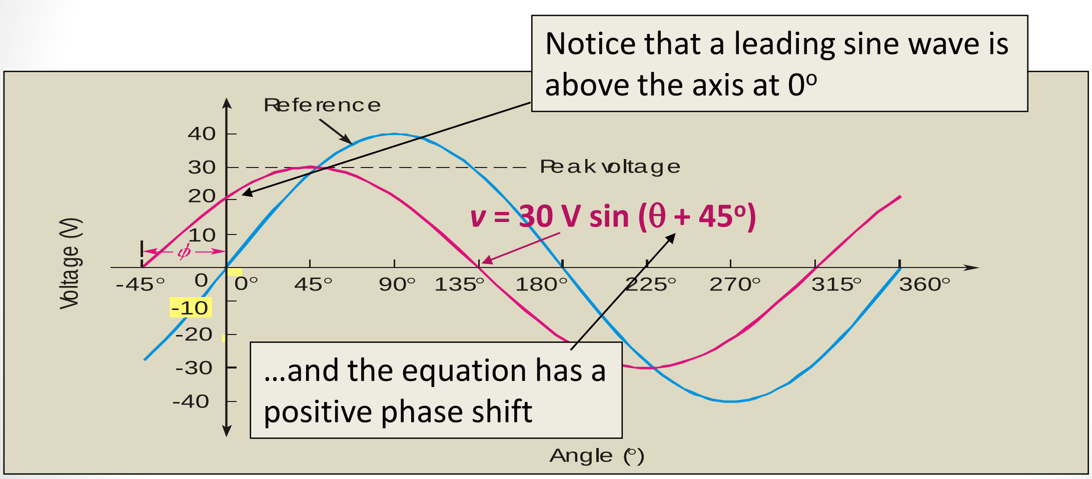
Phase shift

Example of a wave that lags the reference



Phase shift

Example of a wave that leads the reference



Power in resistive AC circuits

The power relationships developed for dc circuits apply to ac circuits except you must use **rms values** in ac circuits when calculating power.

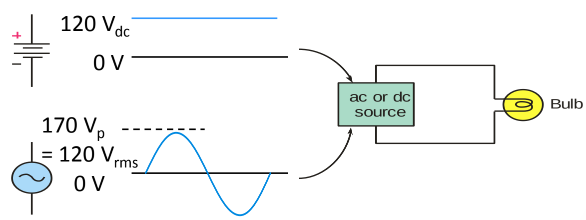
The power formulas are:

$$P = V_{rms} I_{rms}$$

$$P = \frac{V_{rms}^2}{R}$$

$$P = I_{rms}^2 R$$

For example, the dc and the ac sources produce the same power to the bulb:



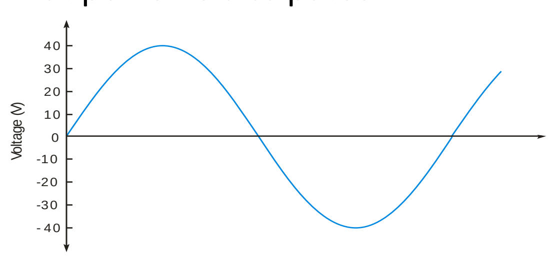
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Power in resistive AC circuits

Example

Assume a sine wave with a peak value of **40 V** is applied to a **100 Ω** resistive load. What power is dissipated?



Solution

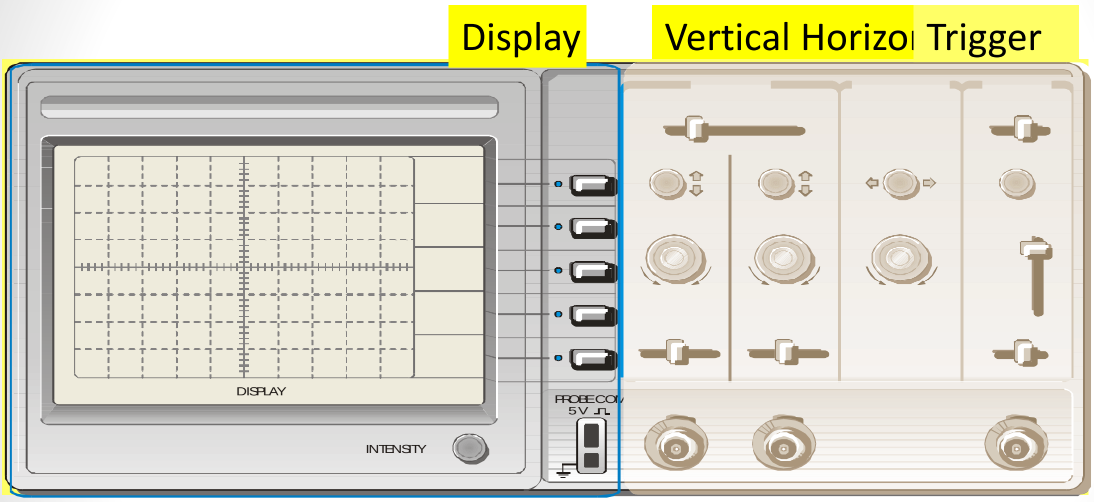
$V_{rms} = 0.707 \times V_p = 0.707 \times 40\text{ V} = 28.3\text{ V}$

$$P = \frac{V_{rms}^2}{R} = \frac{28.3\text{ V}^2}{100\ \Omega} = \mathbf{8\ W}$$

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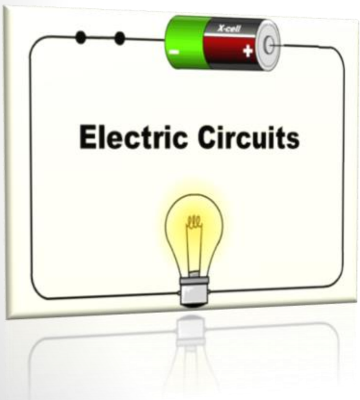
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Oscilloscopes



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Electronic Fundamentals

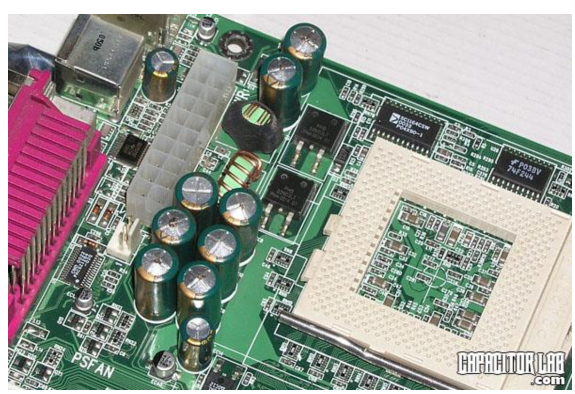
Circuits, Devices, and Applications

Lecture 4: Electric Circuits Essentials Part (4)

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Electric Circuits Essentials Part (4)

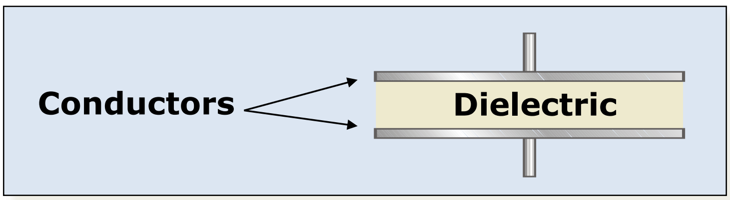
- The Basic Capacitor
- Capacitance
- Series capacitors
- Capacitive reactance
- Capacitive Voltage Divider



The Basic Capacitor

Capacitors are one of the fundamental electric components. In its most basic form, it is composed of two conductive plates separated by an insulating dielectric.

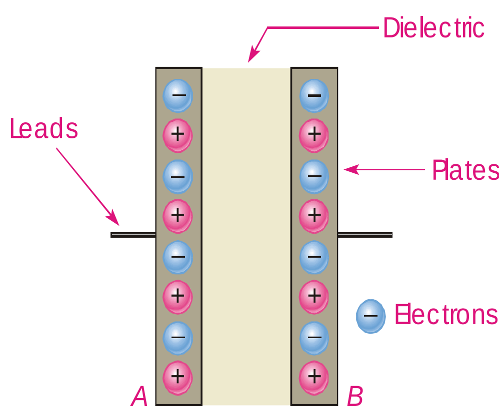
The ability to store charge is the definition of **capacitance**.



The Basic Capacitor

The charging process…

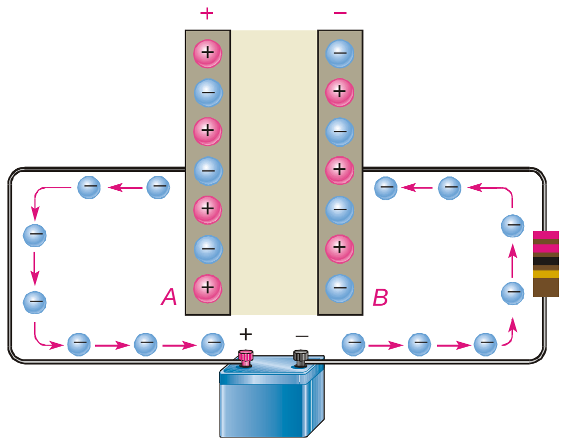
Initially uncharged



The Basic Capacitor

The charging process…

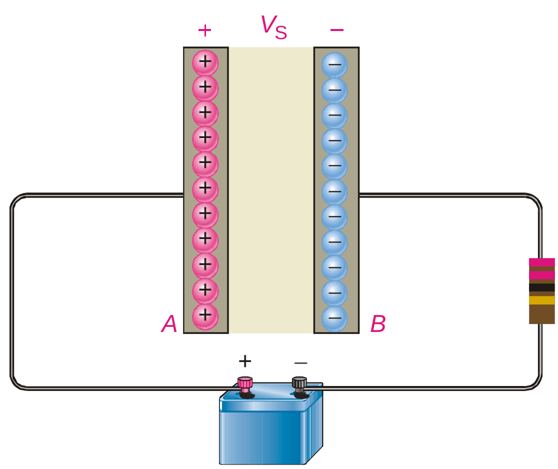
Charging



The Basic Capacitor

The charging process…

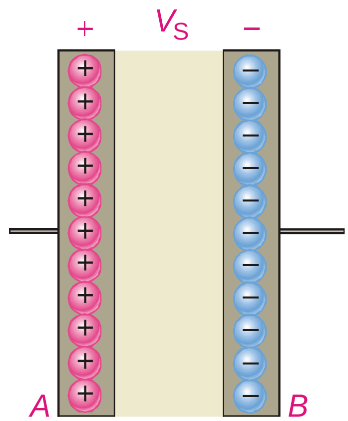
Fully charged



The Basic Capacitor

The charging process…

Source removed



A capacitor with stored charge can act as a temporary battery.

Capacitance

Capacitance is the ratio of charge to voltage

$$C = \frac{Q}{V}$$

Rearranging, the amount of charge on a capacitor is determined by the size of the capacitor (*C*) and the voltage (*V*).

$$Q = CV$$

Example

If a 22 μF capacitor is connected to a 10 V source, the charge is **220 μC**

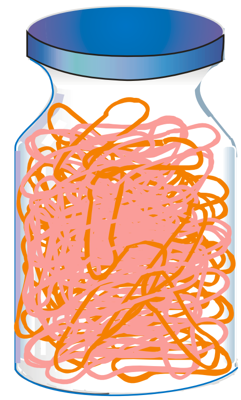
Capacitance

An analogy:

Imagine you store rubber bands in a bottle that is nearly full.

You could store more rubber bands (like charge or *Q*) in a bigger bottle (capacitance or *C*) *or* if you push them in more (voltage or *V*). Thus,

$$Q = CV$$



Capacitance

A capacitor stores **energy** in the form of an **electric field** that is established by the opposite charges on the two plates. The energy of a charged capacitor is given by the equation

$$W = \frac{1}{2}CV^2$$

where

W = the energy in joules
C = the capacitance in farads
V = the voltage in volts

Capacitance

The capacitance of a capacitor depends on three physical characteristics.

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

C is directly proportional to
the **relative dielectric constant**
and the **plate area**.
C is inversely proportional to
the **distance** between the plates

Capacitance

Example Find the capacitance of a 4.0 cm diameter sensor immersed in oil if the plates are separated by 0.25 mm. $(\varepsilon_r = 4.0 \text{ for oil})$

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

The plate area is $A = \pi r^2 = \pi\left(0.02\ \text{m}^2\right) = 1.26\times10^{-3}\ \text{m}^2$

The distance between the plates is $0.25\ ´\ 10^{-3}\ \text{m}$

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{(4.0)\left(1.26\times10^{-3}\ \text{m}^2\right)}{0.25\times10^{-3}\ \text{m}}\right) = \textbf{178 pF}$$

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Series capacitors

When capacitors are connected in series, the total capacitance is smaller than the smallest one. The general equation for capacitors in series is

$$C_T = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots+\frac{1}{C_T}}$$

The total capacitance of two capacitors is

$$C_T = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}}$$

…or you can use the product-over-sum rule

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

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Series capacitors

Example

If a 0.001 μF capacitor is connected in series with an 800 pF capacitor, the total capacitance is **444 pF**



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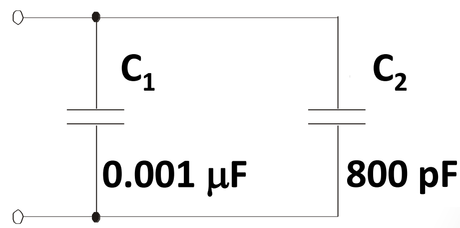
Parallel capacitors

When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors. The general equation for capacitors in parallel is

$$C_T = C_1 + C_2 + C_3 + \ldots C_n$$

Example

If a 0.001 μF capacitor is connected in parallel with an 800 pF capacitor, the total capacitance is 1800 pF



Capacitive reactance

Capacitive reactance is the opposition to ac by a capacitor. The equation for capacitive reactance is

$$X_C = \frac{1}{2\pi f C}$$

Example

The reactance of a 0.047 μF capacitor when a frequency of 15 kHz is applied is **226 Ω**

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Capacitive reactance

When capacitors are in series, **the total reactance is the sum of the individual reactances.** That is,

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3} + \cdots + X_{Cn}$$

Example Assume three 0.033 μF capacitors are in series with a 2.5 kHz ac source. **What is the total reactance?**

Solution: The reactance of each capacitor is

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(2.5\ \text{kHz})(0.033\ \mu\text{F})} = 1.93\ \text{k}\Omega$$

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3}$$

$$= 1.93\ \text{k}\Omega + 1.93\ \text{k}\Omega + 1.93\ \text{k}\Omega = \mathbf{5.79\ k\Omega}$$

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Capacitive reactance

When capacitors are in parallel, **the total reactance is the reciprocal of the sum of the reciprocals of the individual reactances**. That is,

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \cdots + \frac{1}{X_{Cn}}}$$

Example If the three 0.033 μF capacitors from the last example are placed in parallel with the 2.5 kHz ac source, **what is the total reactance?**

Solution: The reactance of each capacitor is 1.93 kΩ

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}}} = \frac{1}{\frac{1}{1.93\ \text{k}\Omega} + \frac{1}{1.93\ \text{k}\Omega} + \frac{1}{1.93\ \text{k}\Omega}} = \mathbf{643\ \Omega}$$

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Capacitive Voltage Divider

Two capacitors in series are commonly used as a capacitive voltage divider. **The capacitors split the output voltage in proportion to their reactance (and inversely proportional to their capacitance).**

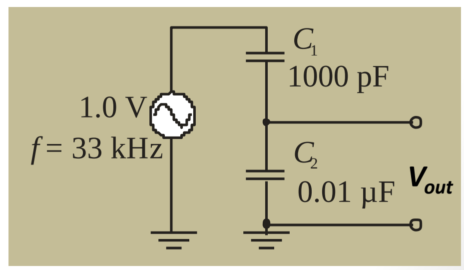
Example **What is the output voltage for the capacitive voltage divider?**

$$X_{C1} = \frac{1}{2\pi f C_1} = \frac{1}{2\pi(33\text{ kHz})(1000\text{ pF})} = 4.82\text{ k}\Omega$$

$$X_{C2} = \frac{1}{2\pi f C_2} = \frac{1}{2\pi(33\text{ kHz})(0.01\text{ }\mu\text{F})} = 482\ \Omega$$

$$X_{C(tot)} = X_{C1} + X_{C2} = 4.82\text{ kW} + 482\text{ W} = 5.30\text{ kW}$$

$$V_{out} = \left(\frac{X_{C2}}{X_{C(tot)}}\right)V_s = \left(\frac{482\ \Omega}{5.30\text{ k}\Omega}\right)1.0\text{ V} = \textbf{91 mV}$$

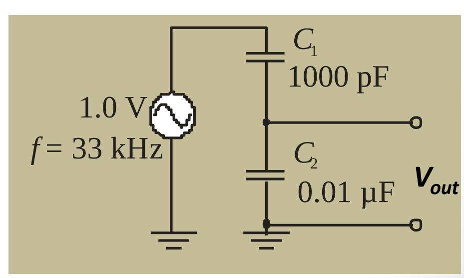


Capacitive Voltage Divider

Instead of using a ratio of reactances in the capacitor voltage divider equation, you can use a ratio of the total series capacitance to the output capacitance (multiplied by the input voltage). The result is the same. For the problem presented in the last slide,

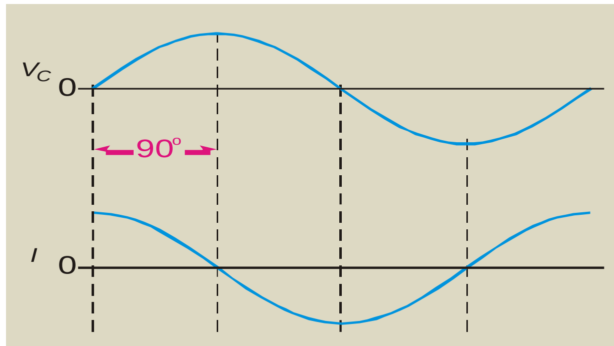
$$C_{(tot)} = \frac{C_1 C_2}{C_1 + C_2} = \frac{(1000\text{ pF})(0.01\text{ }\mu\text{F})}{1000\text{ pF} + 0.01\text{ }\mu\text{F}} = 909\text{ pF}$$

$$V_{out} = \left(\frac{C_{(tot)}}{C_2}\right)V_s = \left(\frac{909\text{ pF}}{0.01\text{ }\mu\text{F}}\right)1.0\text{ V} = \textbf{91 mV}$$



Capacitive phase shift

When a sine wave is applied to a capacitor, there is a phase shift between voltage and current such that current always **leads** the voltage by 90°.



Quiz

1. The capacitance of a capacitor will be larger if
- a. the spacing between the plates is increased.
- b. air replaces oil as the dielectric.
- c. the area of the plates is increased.
- d. all of the above.

1. c

2. The capacitance of two capacitors connected in series will is analogous to
- a. two resistors connected in series
- b. two resistors connected in parallel
- c. none of the above.
- d. all of the above.

2. b

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Quiz

3. If a 0.015 μF capacitor is in series with a 6800 pF capacitor, the total capacitance is

a. 1568 pF.
b. 4678 pF.
c. 6815 pF.
d. 0.022 μF.

3. b

4. Two capacitors that are initially uncharged are connected in series with a dc source. Compared to the larger capacitor, the smaller capacitor will have

a. the same charge.
b. more charge.
c. less voltage.
d. the same voltage.

4. a

Quiz

5. The capacitive reactance of a 100 μF capacitor to 60 Hz is

a. 6.14 kΩ.
b. 265 Ω.
c. 37.7 Ω.
d. 26.5 Ω.

5. d

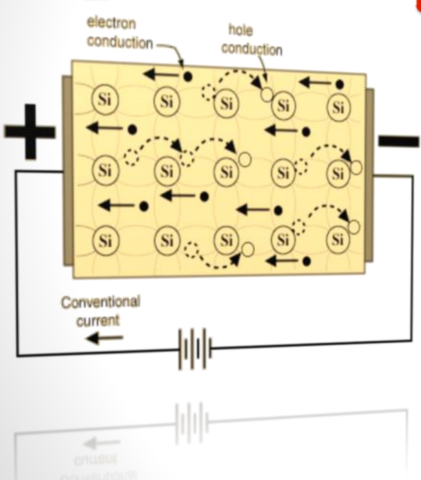
6. If an sine wave from a function generator is applied to a capacitor, the current will

a. lag voltage by 90°.
b. lag voltage by 45°.
c. be in phase with the voltage.
d. none of the above.

6. d

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Electronic Fundamentals

Circuits, Devices, and Applications

Unit 2: Introduction to electronics

Lecture 5: Current in semiconductors

Dr. Hazem Falah Sakeek
Al-Azhar University of Gaza

1

Semiconductors



2

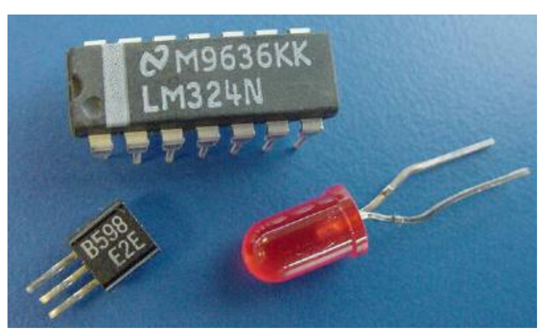
Objectives

The way a material conducts electrical current is important in understanding how electronic devices operate.

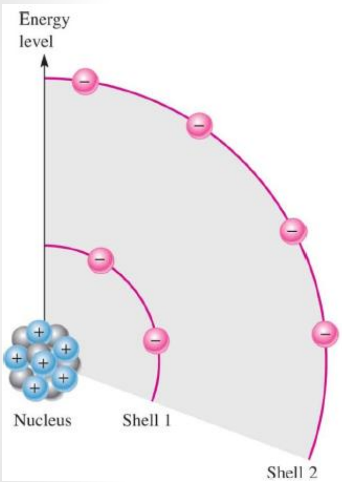
- Understand the basic structure of semiconductors and how they conduct current.
- Describe the properties of *n*-type and *p*-type semiconductors
- Describe how a *pn* junction is formed
- Describe the characteristics and biasing of a pn junction diode.

Unit 2: Introduction to Electronics

- **Materials used in electronics**
- **Current in semiconductors**
- ***N*-type and**
  P-type semiconductors
- **The *pn* junction**



The Atom Properties



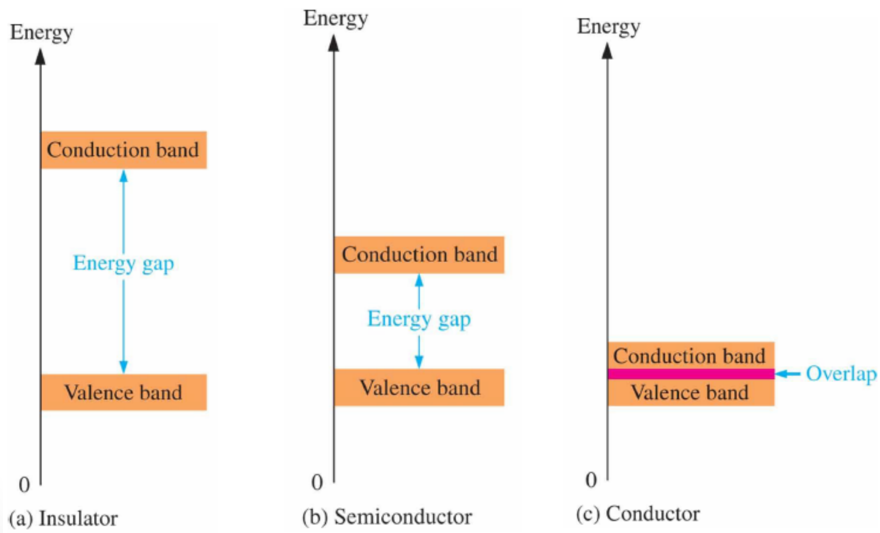
Energy increases as the distance from the nucleus increases.

- Electrons with the highest energy levels exists in the outermost shell of an atom and are loosely bound to the atom.
- This outermost shell is known as the valence shell and electrons in the shell are called valence electrons.
- When an electron gains a certain amount of energy, it moves to an orbit farther from the nucleus.
- The process of losing an electron is called ionization.
- The escaped valence electron is called a free electron.

Insulators, Conductors, and Semiconductors

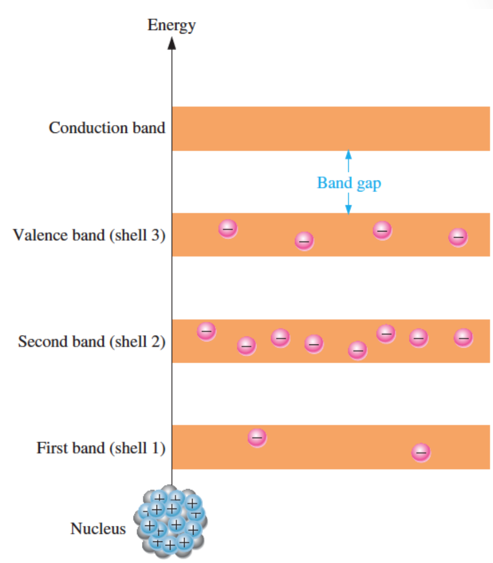
- ***Insulators*** is a material that does not conduct electrical current under normal conditions. Most insulators are compounds and have very high resistivities. Valence electrons are tightly bound to the atoms. Examples of insulators are rubber, plastics, glass, mica, and quartz.
- ***Conductors*** is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as (Cu), (Ag), (Au), and (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom.
- ***Semiconductors*** is a material that is between conductors and insulators in its ability to conduct electrical current. The single-element semiconductors are characterized by atoms with four valence electrons. Silicon is the most commonly used semiconductor.

Energy diagrams



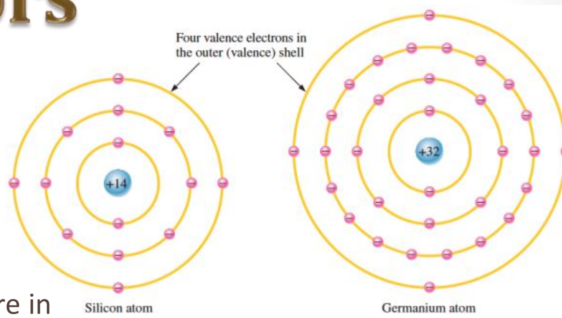
Semiconductors

- Semiconductors are crystalline materials that are characterized by specific energy bands for electrons.
- Between the bands are gaps; these gaps represent energies that electrons cannot have.
- The last energy band is the **conduction band,** where electrons are mobile.
- The next to the last band is the **valence band**, which is the energy level associated with electrons involved in bonding.



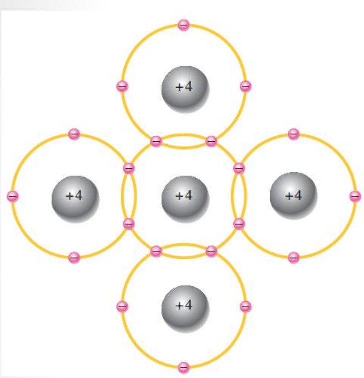
Semiconductors

- Both the **silicon** and **germanium** atoms have four valence electrons.
- These atoms differ in that silicon has 14 protons in its nucleus and germanium has 32.

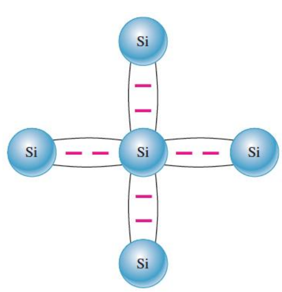


- The valence electrons in germanium are in the **fourth shell** while the ones in silicon are in the **third shell** closer to the nucleus.
- This means that the germanium valence electrons are at a higher energy levels than those in silicon and therefore requires a small amount of additional energy to escape from the atom.
- This property makes germanium more unstable than silicon at high temperatures.

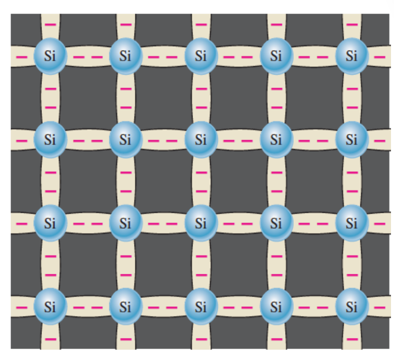
Covalent bonds in a intrinsic silicon crystal



The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



Bonding diagram. The red negative signs represent the shared valence electrons.

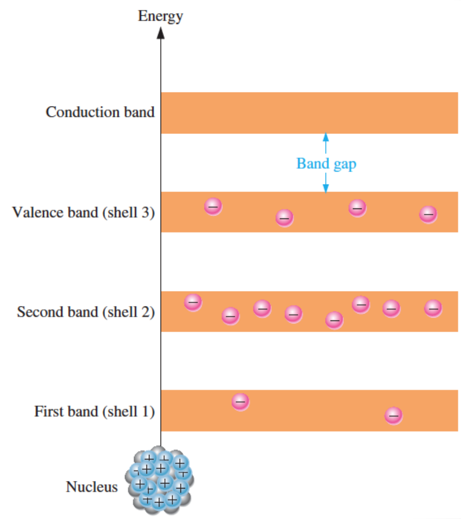


Covalent bonds in a silicon crystal.

Covalent bonding for germanium is similar because it also has four valence electrons.

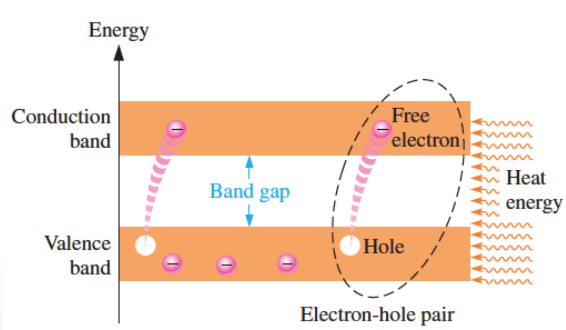
Current in semiconductors

- Each shell around the nucleus corresponds to a certain energy band and is separated from adjacent shells by band gaps, in which no electrons can exist.
- The Figure shows the energy band diagram for an unexcited (no external energy such as heat) atom in a pure (intrinsic) silicon crystal.
- **This condition occurs *only* at a temperature of absolute 0 Kelvin.**

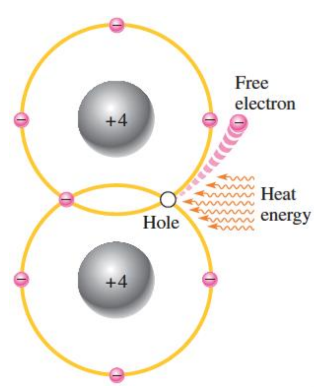


Conduction Electrons and Holes

- An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons.**



Energy diagram



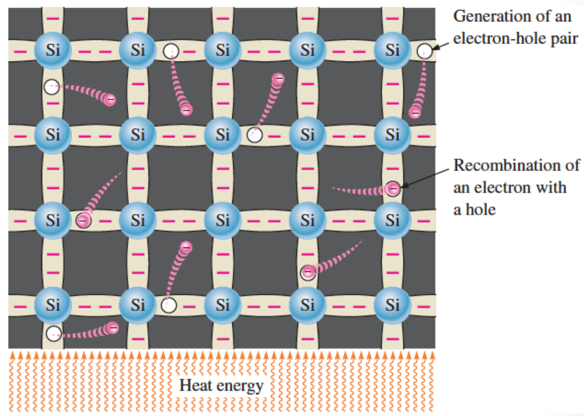
Bonding diagram

Conduction Electrons and Holes

When an **electron jumps** to the conduction band, a **vacancy** is left in the valence band within the crystal.

This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair.**

Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

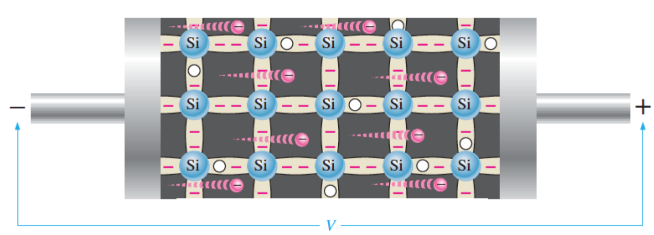


Electron-hole pairs in a silicon crystal.
Free electrons are being generated continuously while some recombine with holes.

Conduction Electrons and Holes

When a **voltage** is applied across a piece of intrinsic silicon, the thermally generated free electrons in the conduction band, which are free to move randomly in the crystal structure, are now easily attracted toward the positive end.

This movement of free electrons is one type of **current** in a semiconductive material and is called ***electron current.***



Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.

Conduction Electrons and Holes

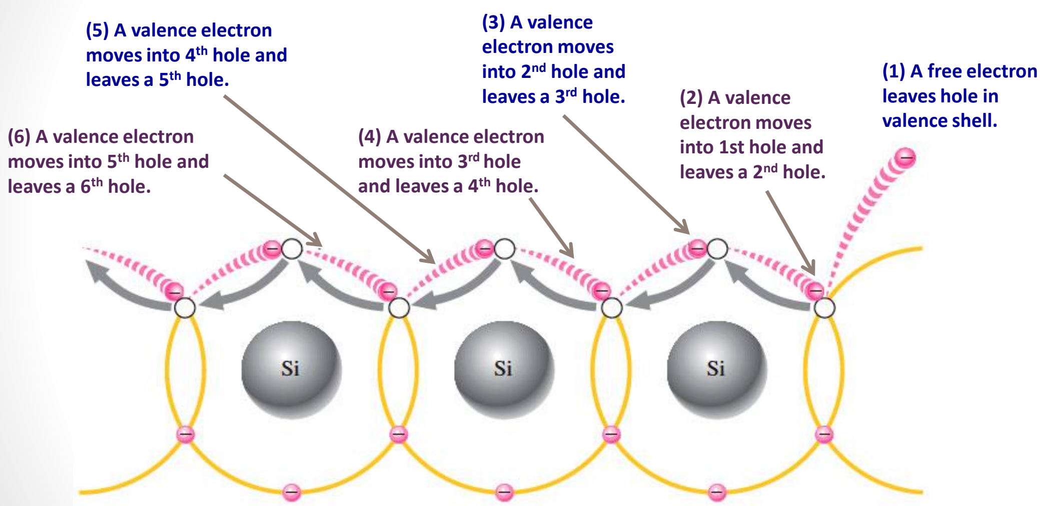
Another type of current occurs in the valence band, where the **holes** created by the free electrons exist.

Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly in the crystal structure as are the free electrons. However, a valence electron can move into a nearby hole, thus leaving another hole where it came from.

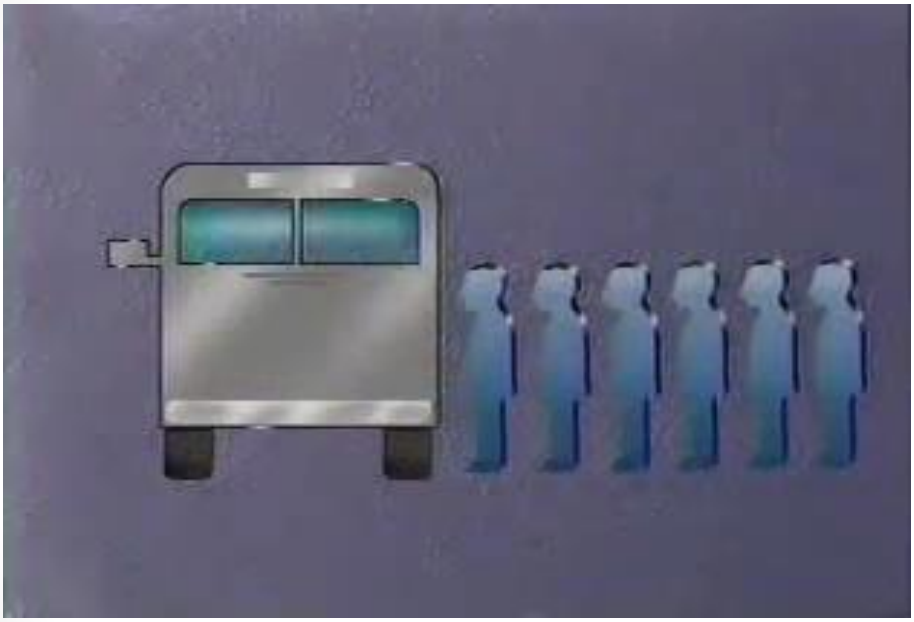
Effectively the hole has moved from one place to another in the crystal structure, as illustrated in Figure.

Although current in the valence band is produced by valence electrons, it is called ***hole current*** to distinguish it from electron current in the conduction band.

Holes Current



When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. **Gray arrows indicate effective movement of a hole.**



Summery

- The electrons in the conduction band and the holes in the valence band are the **charge carriers**.
- Conduction in semiconductors is considered to be either the movement of free electrons in the conduction band or the movement of holes in the valence band, which is actually the movement of valence electrons to nearby atoms, creating hole current in the opposite direction.

Current in the conduction band is by electrons; Current in the valence band is by holes.

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Questions

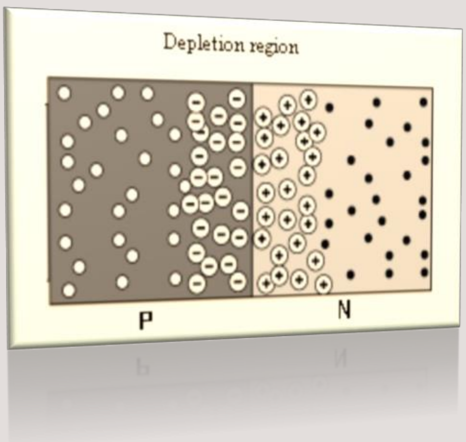
1. What is the basic difference between conductors and insulators?
2. How do semiconductors differ from conductors and insulators?
3. Why does a semiconductor have fewer free electrons than a conductor?
4. How are covalent bonds formed?
5. What is meant by the term intrinsic ?
6. Are free electrons in the valence band or in the conduction band?
7. Which electrons are responsible for electron current in silicon?
8. What is a hole?
9. At what energy level does hole current occur?

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Electronic Fundamentals

Circuits, Devices, and Applications



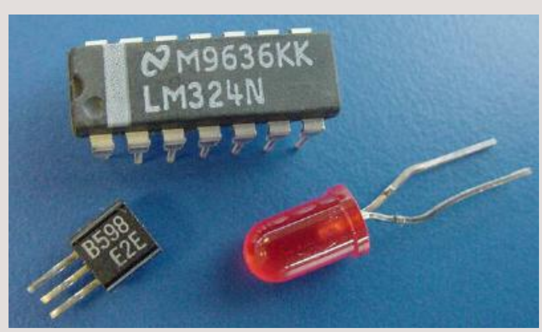
Unit 2: Introduction to electronics

Lecture 6: The pn junction

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Unit 2: Introduction to Electronics

- Materials used in electronics
- Current in semiconductors
- *N*-type and P-type semiconductors
- The *PN* junction



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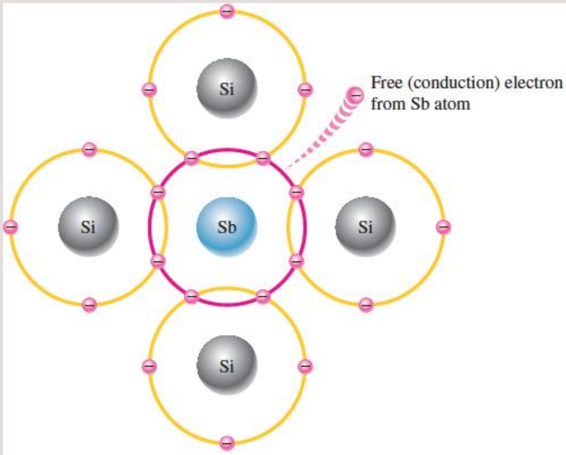
Doping (Adding Impurities)

- Semiconductive materials do not conduct current well and are of limited value in their intrinsic state.
- Intrinsic silicon (or germanium) must be modified by increasing the number of free electrons or holes to increase its conductivity and make it useful in electronic devices.
- This is done by adding impurities to the intrinsic material.
- This process, called **doping**, increases the number of current carriers (electrons or holes).

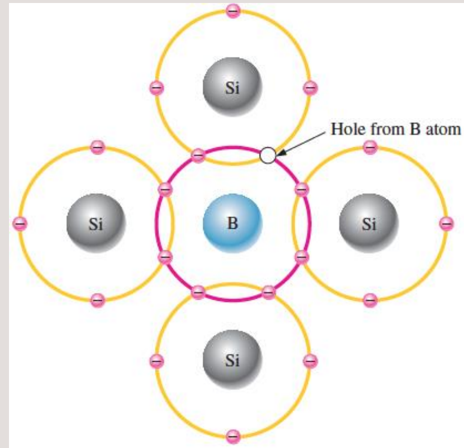
Doping (Adding Impurities)

- By adding certain impurities to pure (intrinsic) silicon, more holes or more electrons can be produced within the crystal.
- To increase the number of conduction band electrons, pentavalent impurities are added, forming an n-type semiconductor. These are elements to the right of Si on the Periodic Table.
- To increase the number of holes, trivalent impurities are added, forming a p-type semiconductor. These are elements to the left of Si on the Periodic Table.

III	IV	V
B	C	N
Al	Si	P
Ga	Ge	As
In	Sn	Sb



Pentavalent impurity atom in a silicon crystal structure. The extra electron from the antimony (Sb) atom becomes a free electron.



Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

N-Type Semiconductor

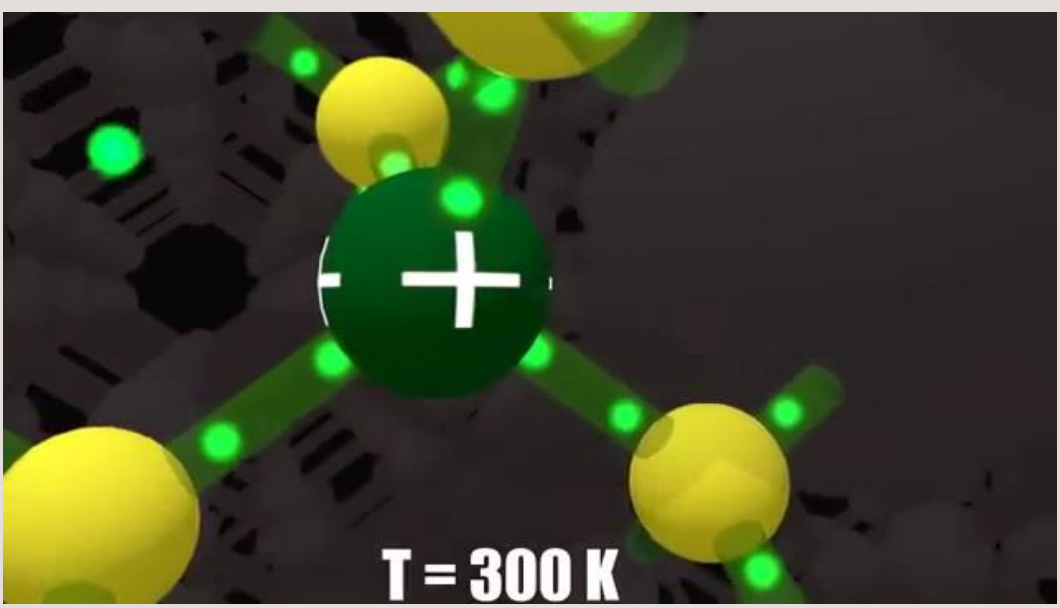
- Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron).
- The **electrons** are called the **majority carriers** in *n*-type material.
- There are also a few holes that are created when electron-hole pairs are thermally generated.
- **Holes** in an *n*-type material are called **minority carriers.**

Because the pentavalent atom gives up an electron, it is often called a ***donor atom***.

P-Type Semiconductor

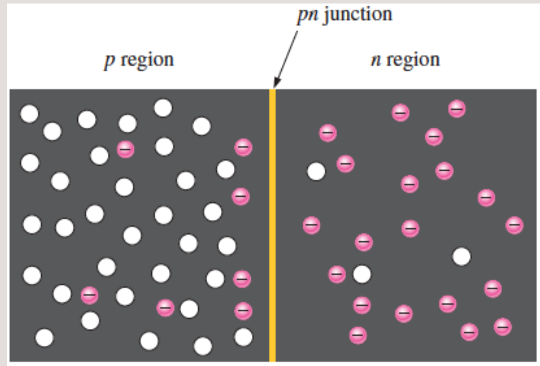
- Since most of the current carriers are holes, silicon (or germanium) doped with trivalent atoms is called a *p*-type semiconductor.
- The **holes** are the **majority carriers** in *p*-type material.
- There are also a few conduction-band electrons that are created when electron-hole pairs are thermally generated.
- Conduction-band **electrons** in *p*-type material are the **minority carriers**.

Because the trivalent atom can take an electron, it is often referred to as an ***acceptor atom***.



The PN Junction

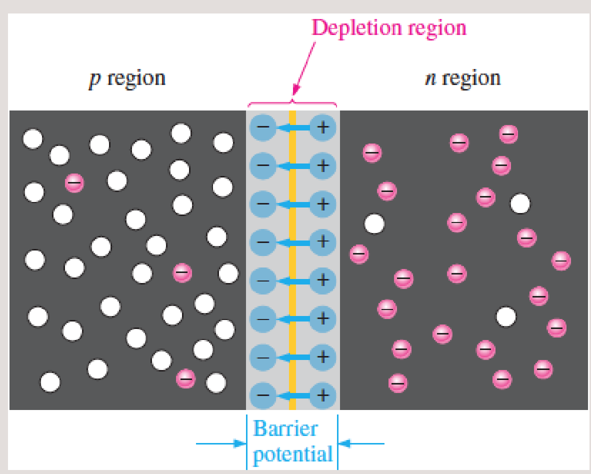
- When you take a block of silicon and dope part of it with a trivalent impurity and the other part with a pentavalent impurity, a boundary called the ***pn* junction** is formed between the resulting *p*-type and *n*-type portions.
- **The *PN* junction is the basis for diodes, transistors, solar cells, and other devices.**

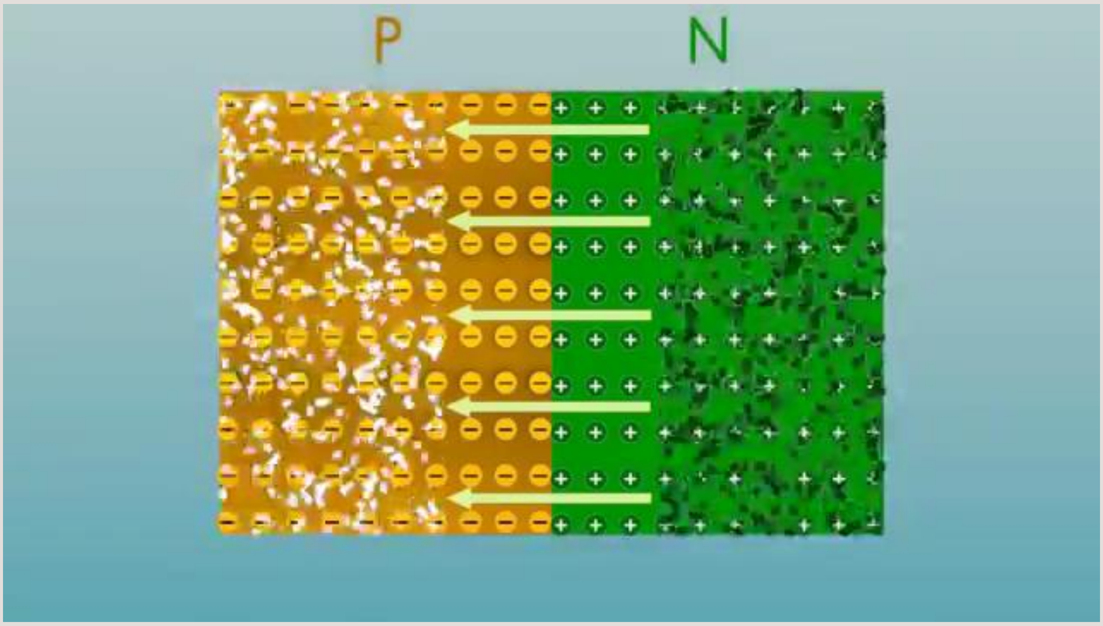


The basic silicon structure at the **instant** of junction formation showing only the majority and minority carriers.

Formation of the Depletion Region

At the **instant** of the *pn* junction formation, the free electrons near the junction in the *n* region begin to **diffuse** across the junction into the *p* region where they **combine** with holes near the junction.





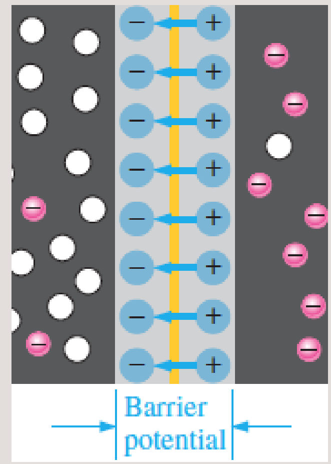
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- **Before** the *pn* junction is formed, there are as many electrons as protons in the *n*-type material, making the **material neutral** in terms of net charge. The same is true for the *p*-type material.
- **After** the *pn* junction is formed, the ***n* region loses free electrons** as they diffuse across the junction.
- This creates a layer of **positive charges** (pentavalent ions) near the junction.
- As the electrons move across the junction, the *p* region loses holes as the electrons and holes combine.
- This creates a layer of **negative charges** (trivalent ions) near the junction.
- These two layers of positive and negative charges form the **depletion region.**
- **In the end equilibrium is established and there is no further diffusion of electrons across the junction.**

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Barrier Potential

- An ***electric field*** *is established in* the depletion region.
- This electric field is a barrier to the free electrons in the *n* region, and energy must be expended to move an electron through the electric field.
- This potential difference is called the **barrier potential** and is expressed in volts. (0.7 V for silicon and 0.3 V for germanium at 25°C).

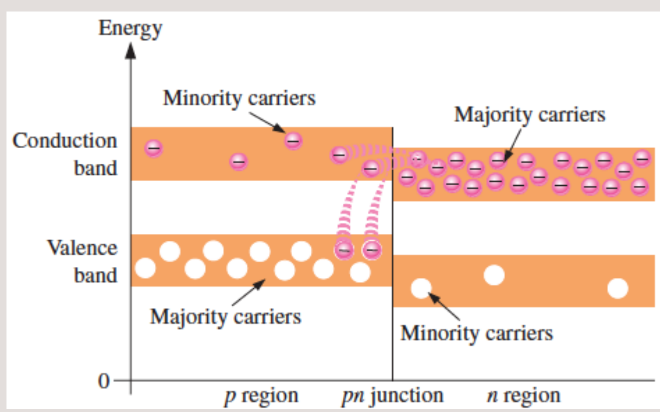


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Energy Diagrams

The valence and conduction bands in the *n* region are at lower energy levels than those in the *p* region, but there is a significant amount of overlapping.



The free **electrons** in the *n* region that occupy the **upper part** of the conduction band in terms of their energy can easily **diffuse** across the junction and temporarily become free electrons in the **lower part** of the *p*-region conduction band. After crossing the junction, the electrons quickly lose energy and **fall into** the holes in the *p*-region valence band.

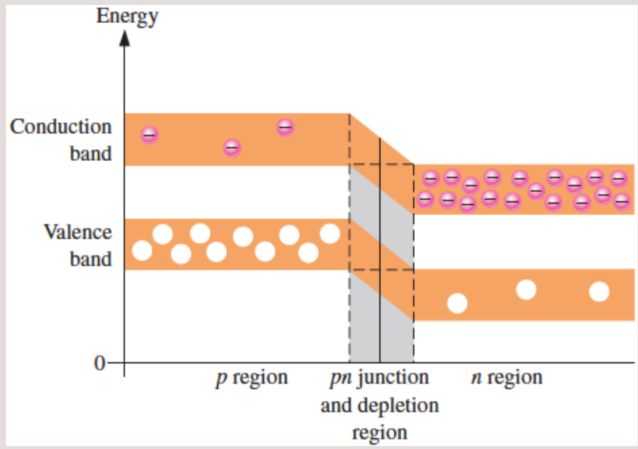
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As the diffusion continues, the depletion region begins to form and the energy level of the *n*-region conduction band decreases.

The decrease in the energy level of the conduction band in the *n* region is due to the **loss of the higher-energy electrons** that have diffused across the junction to the *p* region.

After the depletion region is formed, there are no electrons left in the *n*-region conduction band with enough energy to get across the junction to the *p*-region conduction band, as indicated by the alignment of the top of the *n*-region conduction band and the bottom of the *p*-region conduction band.



Summary

- An *n*-type semiconductive material is created by adding impurity atoms that have five valence electrons. A *p*-type semiconductor is created by adding impurity atoms with only three valence electrons.
- The process of adding pentavalent or trivalent impurities to a semiconductor is called ***doping***.
- A *pn* junction is formed when part of a material is doped *n*-type and part of it is doped *p*-type. A depletion region forms starting at the junction that is devoid of any majority carriers. The depletion region is formed by ionization.
- The barrier potential is typically 0.7 V for a silicon diode and 0.3 V for germanium.

Review Questions

- Define doping.
- How is an n -type semiconductor formed?
- By what process are the majority carriers produced?
- By what process are the minority carriers produced?
- 10. What is the difference between intrinsic and extrinsic semiconductors?
- What is a pn junction?
- Explain diffusion.
- Describe the depletion region.
- Explain what the barrier potential is and how it is created.

Self-test

Try to solve the Self-test in your text book

Electronic Devices

by

Floyd

9th Edition

Pages 21-23



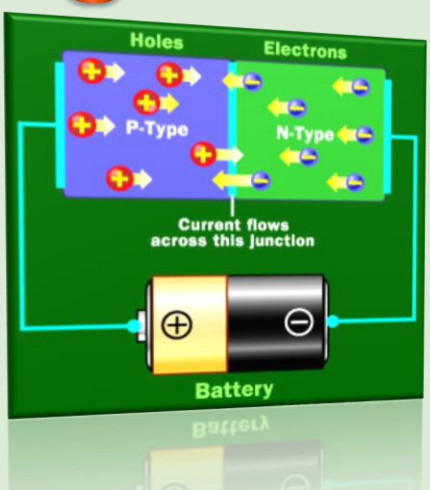
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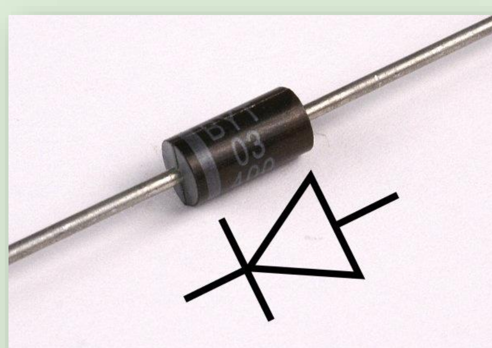
Unit 3: Diodes and Applications

Lecture 7: Diode Operation & V-I Characteristics of a Diode

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Unit 3: Diodes and Applications

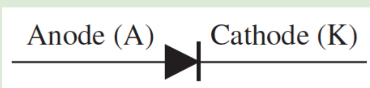
- Diode Operation
- *V-I* Characteristics of a Diode
- Diode Models
- Half-Wave and Full-Wave Rectifiers
- Power Supply Filters and Regulators
- Diode Limiters and Clampers
- Voltage Multipliers



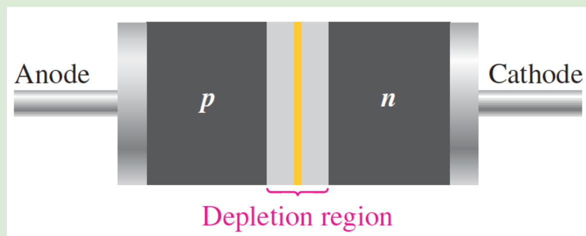
The Diode

Diode is made from a small piece of semiconductor material, usually silicon, in which half is doped as a *p* region and half is doped as an *n* region with a *pn* junction and depletion region in between.

The *p* region is called the **anode** and is connected to a conductive terminal. The *n* region is called the **cathode** and is connected to a second conductive terminal.



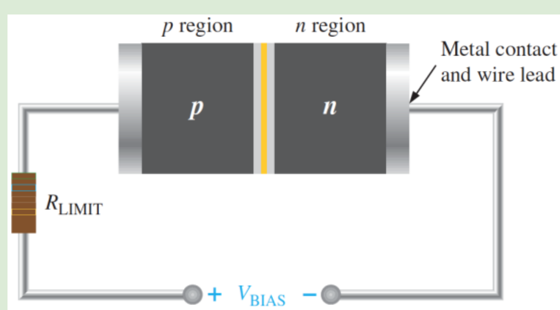
Diode Symbol



Forward Bias

- **Forward bias** is the condition that allows current through the *pn* junction.

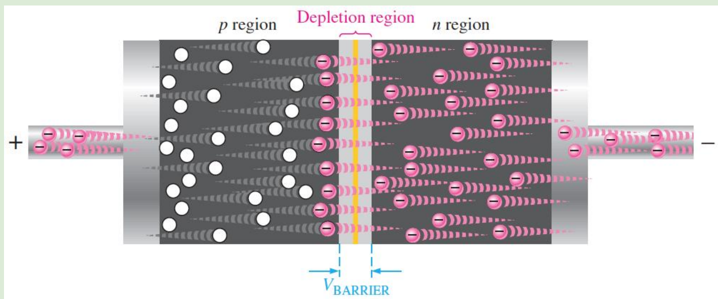
- **Notice** that the negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region.



- V_{BIAS}, must be **greater** than the **barrier potential**.

What happens when a diode is forward-biased?

- The bias-voltage source imparts sufficient energy to the free electrons to overcome the barrier potential of the depletion region and move on through into the *p* region.
- Once in the *p* region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.
- The positive side of the bias-voltage source attracts the valence electrons toward the left end of the *p* region.
- The valence electrons move from one hole to the next toward the left.
- As the electrons flow out of the *p* region, they leave holes behind in the *p* region.

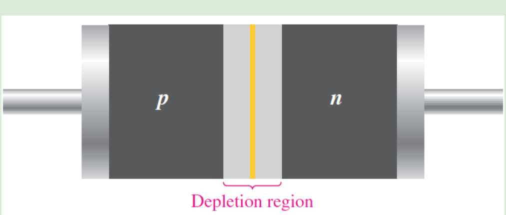


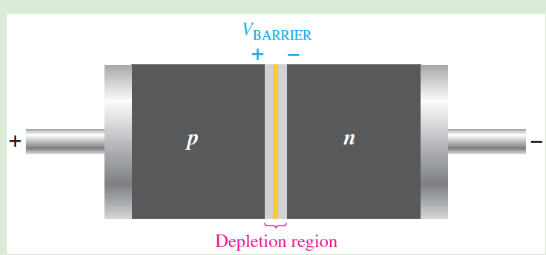
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The Effect of Forward Bias on the Depletion Region

- Under the electrons flow into the depletion region, the number of positive ions is reduced.
- As more holes effectively flow into the depletion region, the number of negative ions is reduced.
- This reduction in positive and negative ions during forward bias causes the **depletion region** to **narrow**.



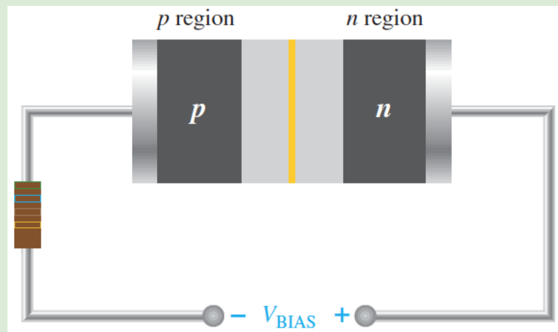


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Reverse Bias

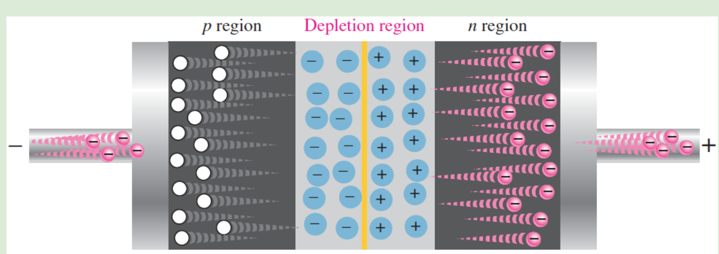
- **Reverse bias** is the condition that essentially prevents current through the diode.
- Notice that the positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region.



- Note that the **depletion region** is shown much **wider** than in forward bias or equilibrium.

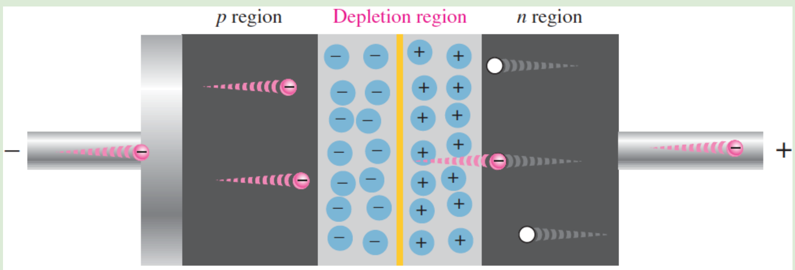
What happens when a diode is Reverse-biased?

- **In the *n* region,** as the electrons flow toward the positive side of the voltage source, additional **positive** ions are created. This results in a **widening** of the depletion region and a depletion of majority carriers.
- **In the *p* region,** electrons from the negative side of the voltage source move from hole to hole toward the depletion region where they create additional **negative** ions. This results in a **widening** of the depletion region and a depletion of majority carriers.
- As more of the *n* and *p* regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, V_{BIAS}.
  At this point, the transition current essentially stops.



Reverse Current

- There is an extremely **small current** that exists in reverse bias after the transition current dies out is caused by the minority carriers in the *n* and *p* regions that are produced by thermally generated electron-hole pairs.
- The conduction band in the *p* region is at a **higher energy level** than the conduction band in the *n* region. Therefore, the minority electrons easily pass through the depletion because they require no additional energy.



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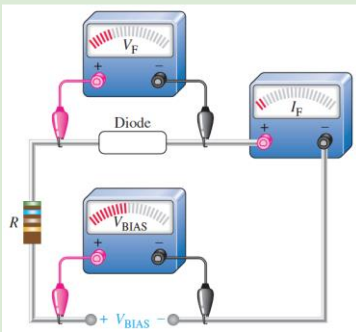
Reverse Breakdown

- If the external reverse-bias voltage is **increased** to a value called the ***breakdown voltage***, the reverse current will drastically increase.
- The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the *p* region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band.
- The newly created conduction electrons are also high in energy and repeat the process.
- The multiplication of conduction electrons is known as the **avalanche effect,**

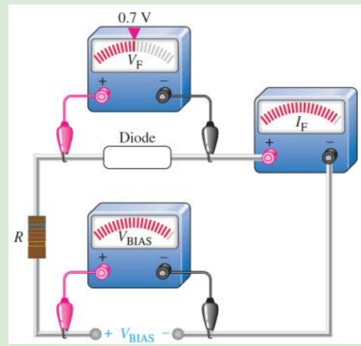
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V-I Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is current. This current is called the ***forward current (I_F)***.



Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

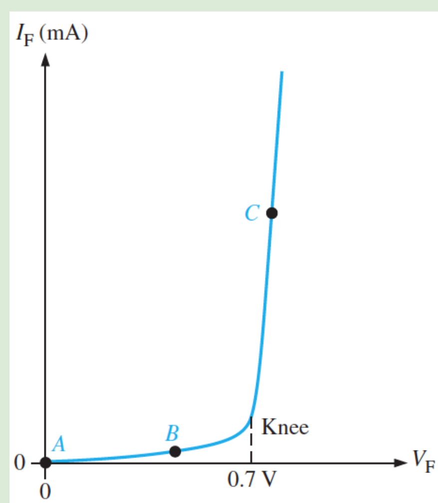


Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

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Graphing *the V-I Curve*

- The diode forward voltage (V_F) increases to the right along the horizontal axis, and the forward current (I_F) increases upward along the vertical axis.
- **Point *A*** corresponds to a zero-bias condition.
- **Point *B*** where the forward voltage is less than the barrier potential of 0.7 V.
- **Point *C*** where the forward voltage *approximately* equals the barrier potential.
- As the external bias voltage and forward current continue to increase above the knee, the forward voltage will increase slightly above 0.7 V.



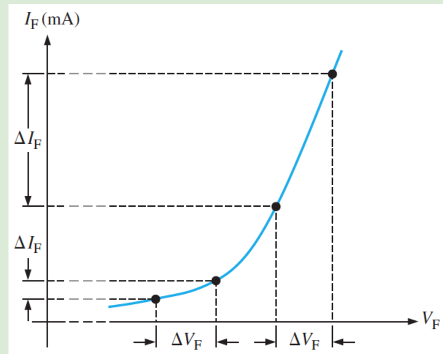
V-I characteristic curve for forward bias

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Dynamic Resistance

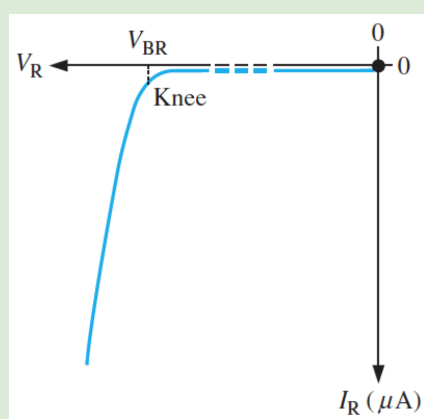
- The resistance of the forward-biased diode is **not constant** over the entire curve. It is called *dynamic* or *ac resistance* r'_d.
- **Below the knee** of the curve the resistance is **greatest** because the current increases very little for a given change in voltage ($r'_d = \Delta V_F / \Delta I_F$).
- The resistance begins to **decrease** in the region of the knee of the curve and becomes smallest above the knee where there is a large change in current for a given change in voltage.



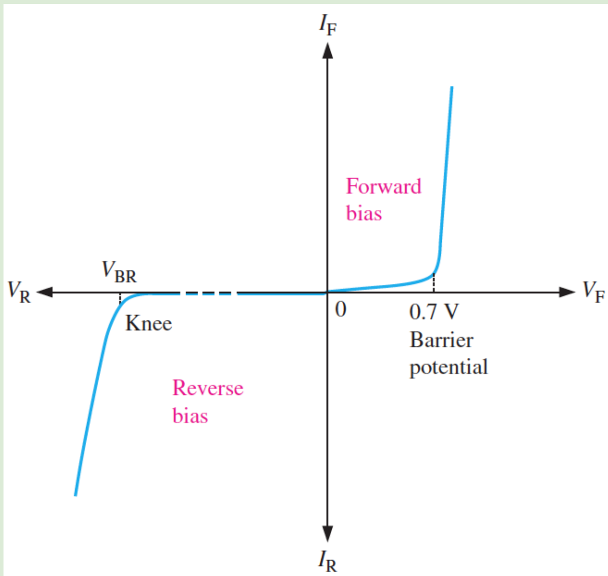
Expanded view of a portion of the previous curve

V-I Characteristic for Reverse Bias

- When a reverse-bias voltage is applied across a diode, there is only an extremely small **reverse current (I_R)** through the *pn* junction.
- **At 0 V** across the diode, no reverse current.
- As you gradually **increase V_R**, there is a very small reverse current and the voltage across the diode increases.
- When the applied bias voltage is increased to a value where (V_R) reaches the breakdown value (V_{BR}), the **I_R begins to increase rapidly**.
- As you continue to increase the V_R, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR}.



The Complete *V-I* Characteristic Curve



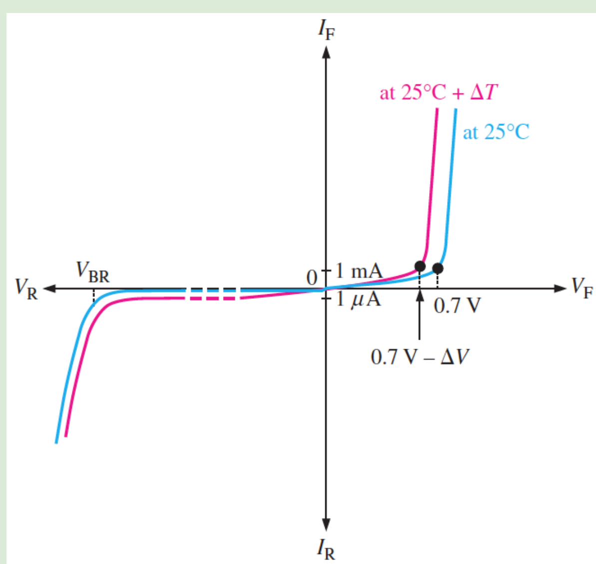
Temperature Effects

For a forward-biased diode, as temperature is increased, the forward current increases. Also, the forward voltage decreases.

The barrier potential decreases by 2 mV for each degree increase in temperature.

For a reverse-biased diode, as temperature is increased, the reverse current increases.

Note: the reverse current below breakdown remains extremely small and can usually be neglected.

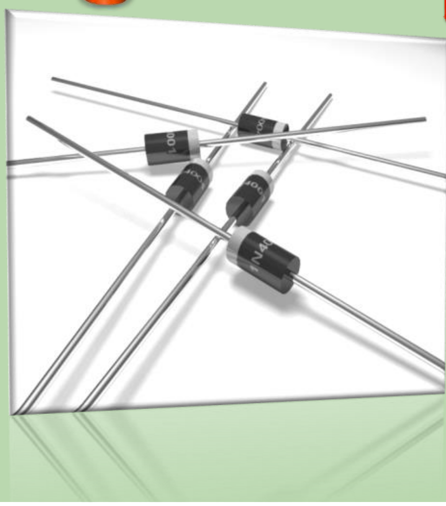


Review Questions

1. Compare the depletion regions in forward bias and reverse bias.
2. When does reverse breakdown occur in a diode?
3. Discuss the significance of the knee of the characteristic curve in forward bias.
4. On what part of the curve is a forward-biased diode normally operated?
5. Which is greater, the breakdown voltage or the barrier potential?
6. What happens to the barrier potential when the temperature increases?

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Electronic Fundamentals

Circuits, Devices, and Applications

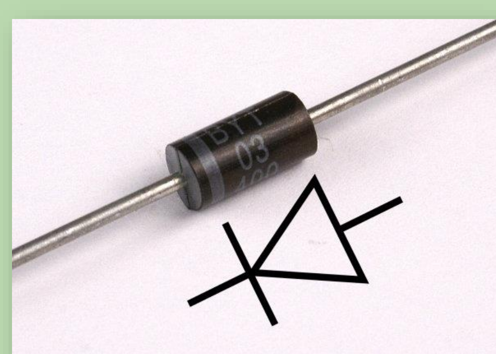
Unit 3: Diodes and Applications

Lecture 8: Diode Models

Dr. Hazem Falah Sakeek
Al-Azhar University of Gaza

Unit 3: Diodes and Applications

- Diode Operation
- *V-I* Characteristics of a Diode
- Diode Models
- Half-Wave and Full-Wave Rectifiers
- Power Supply Filters and Regulators
- Diode Limiters and Clampers
- Voltage Multipliers

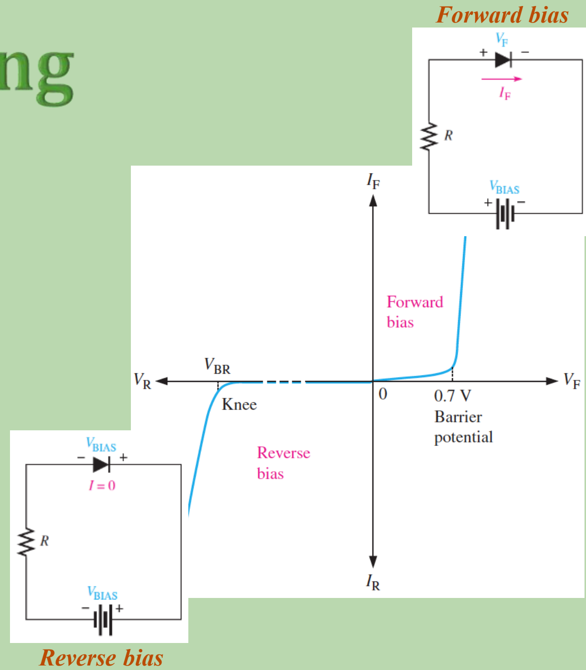


Diode modelling

In electronics, **diode modelling** refers to the mathematical models used to approximate the actual behavior of **real diodes** to enable calculations and circuit analysis.

A diode's I-V curve is nonlinear (it is well described by the Shockley diode law).

This nonlinearity complicates calculations in circuits involving diodes so simpler models are often required.



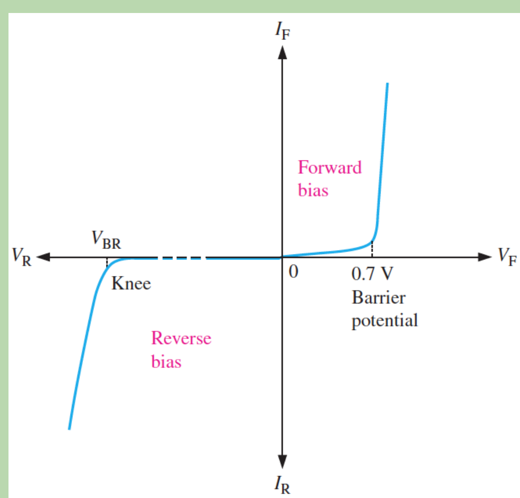
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Shockley diode model

The Shockley diode equation relates the diode current (I_D) of a p-n junction diode to the diode voltage (V_D). This relationship is the diode *I-V characteristic*:

$$I_D = I_s(e^{kV_D/T_K} - 1)$$

I_s = reverse saturation current
k = 11,600/η
η = 1 for Ge and **η = 2** for Si for below the knee of the curve,
η = 1 for both Ge and Si above the knee.
$T_K = T_C + 273^o$



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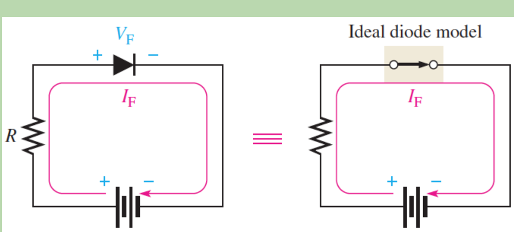
Diode Models

Diode Approximations
- *The Ideal Diode Model*
- *The Practical Diode Model*
- *The Complete Diode Model*

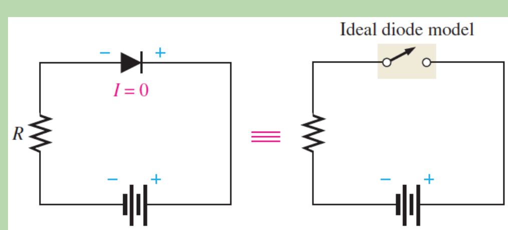
Barrier potential | **Reverse current** | **Dynamic resistance**

The Ideal Diode Model

- The ideal model of a diode is the least accurate approximation and can be represented by a **simple switch**.
- When the diode is forward-biased, it ideally acts like a closed (on) switch
- When the diode is reverse-biased, it ideally acts like an open (off) switch.



Forward bias



Reverse bias

The diode is assumed to have a zero voltage across it when forward-biased, as indicated by the portion of the curve on the positive vertical axis.

$$V_F = 0\text{ V}$$

The forward current is determined by the bias voltage and the limiting resistor using Ohm's law.

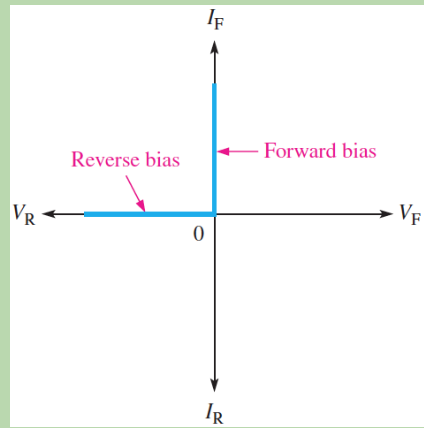
$$I_F = \frac{V_{BIAS}}{R_{LIMIT}}$$

The reverse current is neglected

$$I_R = 0\text{ A}$$

The reverse voltage equals the bias voltage.

$$V_R = V_{BIAS}$$



Ideal V-I characteristic curve

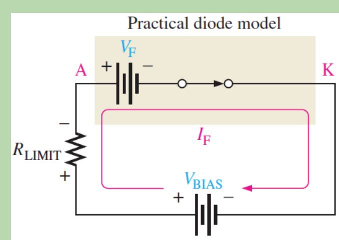
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The Practical Diode Model

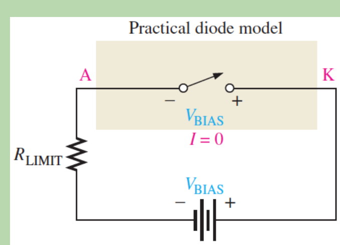
- The practical model includes the **barrier potential**.
- When the diode is **forward-biased**, it is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode.

Note: This equivalent voltage source represents the **barrier potential** that must be exceeded by the bias voltage before the diode will conduct and **is not an active source of voltage.**

- When conducting, a voltage drop of 0.7 V appears across the diode.
- When the diode is **reverse-biased**, it is equivalent to an open switch just as in the ideal model.



Forward bias



Reverse bias

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Since the **barrier potential** is included, the diode is assumed to have a voltage across it when forward-biased, as indicated by the portion of the curve to the right of the origin.

$$V_F = 0.7V$$

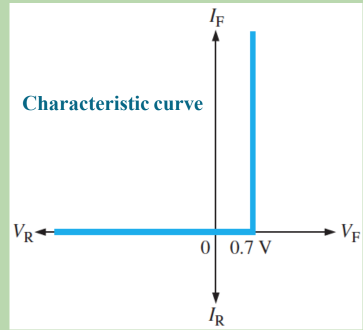
The **forward current** is determined as follows by first applying Kirchhoff's voltage law

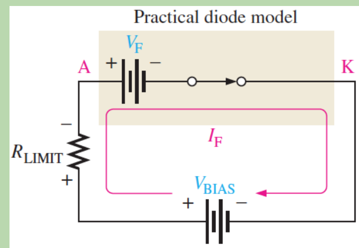
$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

$$I_R = 0\ A$$

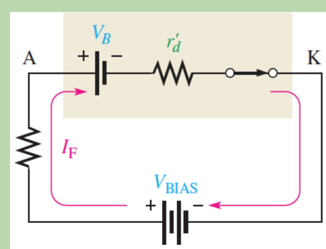
$$V_R = V_{BIAS}$$

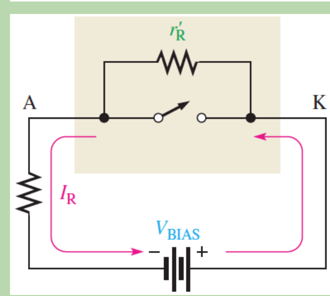




The Complete Diode Model

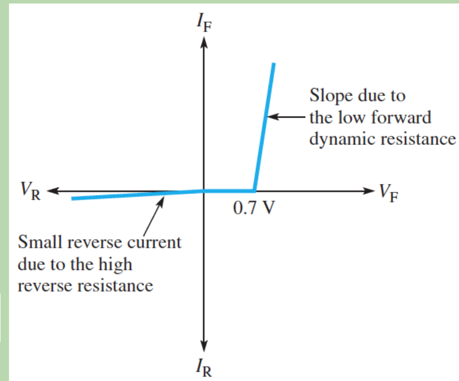
- When the diode is forward-biased, it acts as a closed switch in series with the equivalent **barrier potential voltage (V_B)** and the small forward **dynamic resistance (r'_d)**.
- When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance (r'_R).
- The barrier potential does not affect reverse bias, so it is not a factor.





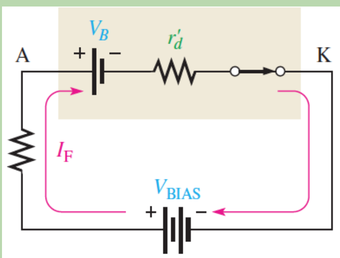
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The curve slopes because the voltage drop due to dynamic resistance increases as the current increases.



The characteristic curve for the complete diode model

$$V_F = 0.7\text{ V} + I_F r'_d$$

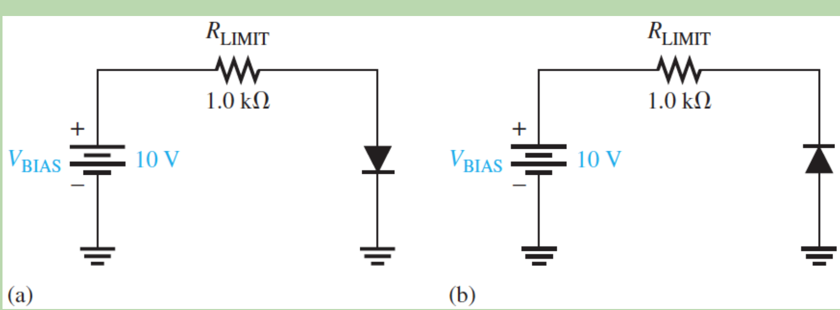


$$I_F = \frac{V_{BIAS} - 0.7\text{ V}}{R_{LIMIT} + r'_d}$$

Example

(a) Determine the **forward voltage** and **forward current** for the diode in Figure (a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume r'_d = 10 ohm at the determined value of forward current.

(b) Determine the **reverse voltage** and **reverse current** for the diode in Figure (b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume I_R = 1 *u*A.



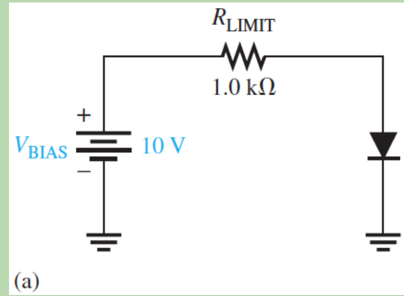
Solution (a)

- **Ideal model:**

$V_F = \mathbf{0\ V}$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10\text{ V}}{1.0\text{ k}\Omega} = \mathbf{10\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10\text{ mA})(1.0\text{ k}\Omega) = \mathbf{10\ V}$$



- **Practical model:**

$V_F = \mathbf{0.7\ V}$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega} = \frac{9.3\text{ V}}{1.0\text{ k}\Omega} = \mathbf{9.3\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9.3\ V}$$

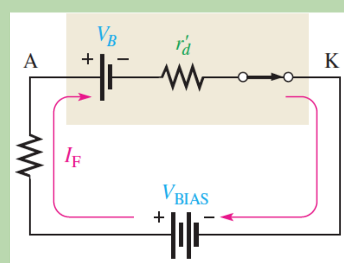
Solution (a)

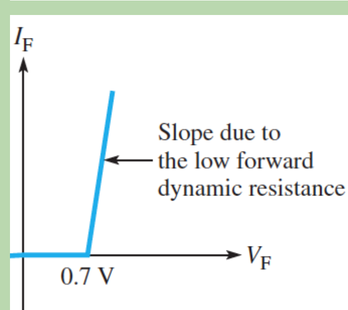
- **Complete model:**

$$I_F = \frac{V_{BIAS} - 0.7\text{ V}}{R_{LIMIT} + r'_d} = \frac{10\text{ V} - 0.7\text{ V}}{1.0\text{ k}\Omega + 10\ \Omega} = \frac{9.3\text{ V}}{1010\ \Omega} = \mathbf{9.21\ mA}$$

$$V_F = 0.7\text{ V} + I_F r'_d = 0.7\text{ V} + (9.21\text{ mA})(10\ \Omega) = \mathbf{792\ mV}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.21\text{ mA})(1.0\text{ k}\Omega) = \mathbf{9.21\ V}$$





Solution (b)

- **Ideal model:**

$I_R = \mathbf{0\,A}$

$V_R = V_{BIAS} = \mathbf{10\,V}$

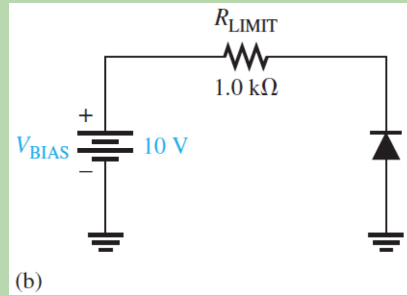
$V_{R_{LIMIT}} = \mathbf{0\,V}$

- **Practical model:**

$I_R = \mathbf{0\,A}$

$V_R = V_{BIAS} = \mathbf{10\,V}$

$V_{R_{LIMIT}} = \mathbf{0\,V}$

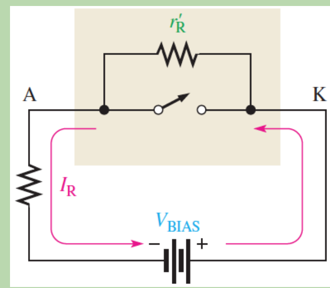


- **Complete model:**

$I_R = \mathbf{1\,\mu A}$

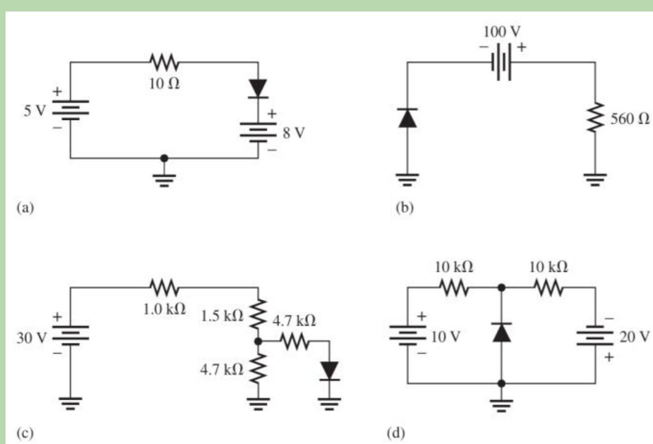
$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\,\mu A)(1.0\,k\Omega) = \mathbf{1\,mV}$

$V_R = V_{BIAS} - V_{R_{LIMIT}} = 10\,V - 1\,mV = \mathbf{9.999\,V}$



Exercise

1. Determine whether each silicon diode in Figure is forward-biased or reverse-biased.
2. Determine the voltage across each diode in Figure, assuming the practical model.
3. Determine the voltage across each diode in Figure, assuming an ideal diode.
4. Determine the voltage across each diode in Figure, using the complete diode model with r'_d = 10 ohm, r'_R = 100 Mohm.

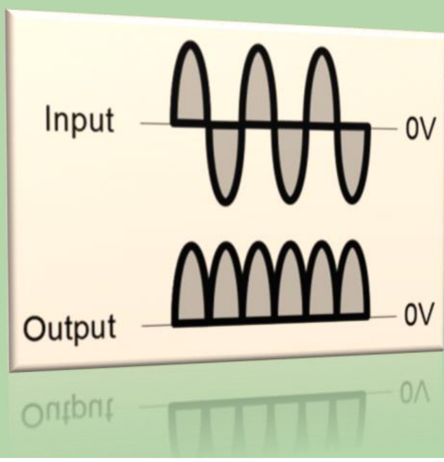


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Electronic Fundamentals

Circuits, Devices, and Applications



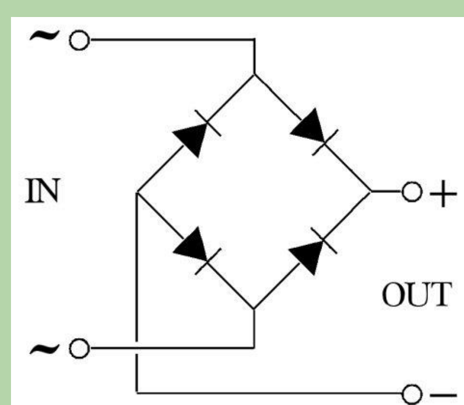
Unit 3: Diodes and Applications

Lecture 9: Half-Wave and Full-Wave Rectifiers

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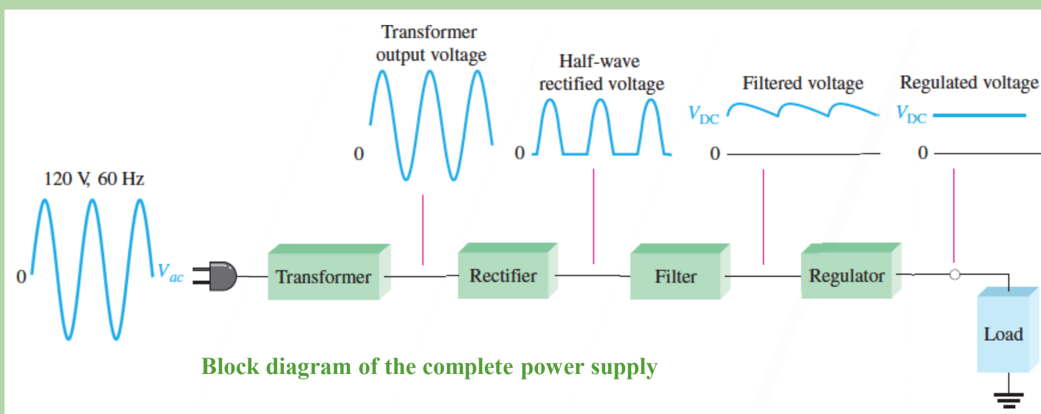
Unit 3: Diodes and Applications

- Diode Operation
- *V-I* Characteristics of a Diode
- Diode Models
- Half-Wave and Full-Wave Rectifiers
- Power Supply Filters and Regulators
- Diode Limiters and Clampers
- Voltage Multipliers



The Basic DC Power Supply

The **dc power supply** converts the standard 220 V, 60 Hz ac voltage available at wall outlets into a constant dc voltage.



Block diagram of the complete power supply

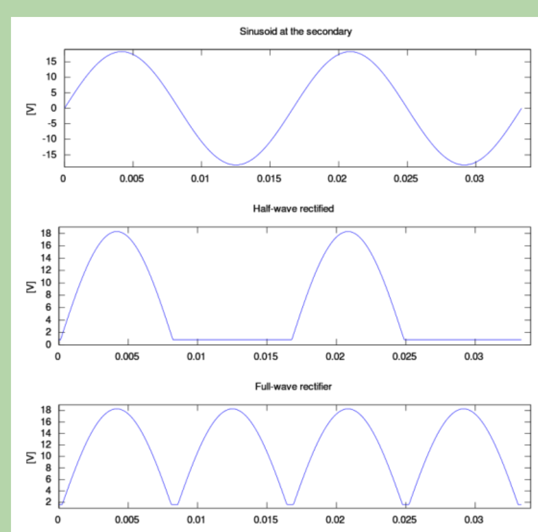
Rectifier

Rectifier are circuit that convert ac to dc.

Special diodes, called rectifier diodes, are designed to handle the higher current requirements in these circuits.

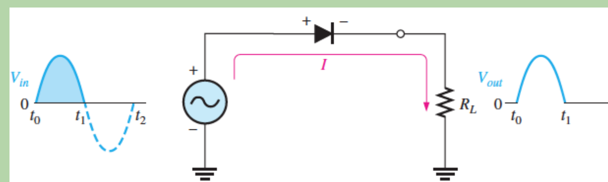
Half-Wave Rectifier

Full-Wave Rectifier

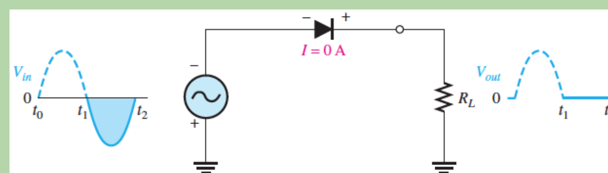


Half-Wave Rectifier Operation

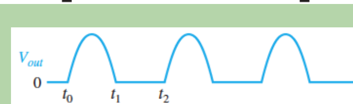
During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage.



During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.



60 Hz half-wave output voltage for three input cycles.



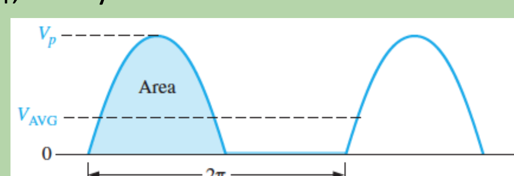
The net result is that only the positive half-cycles of the ac input voltage appear across the load.

Average Value of the Half-Wave Output Voltage

- The average value of the half-wave rectified output voltage is the value you would measure on a dc voltmeter.
- Mathematically, it is determined by finding the area under the curve over a full cycle, and then dividing by 2π, full cycle.

$$V_{AVG} = \frac{V_p}{\pi}$$

V_{AVG} is approximately 31.8% of V_p



Example: What is the average value of the half-wave rectified voltage

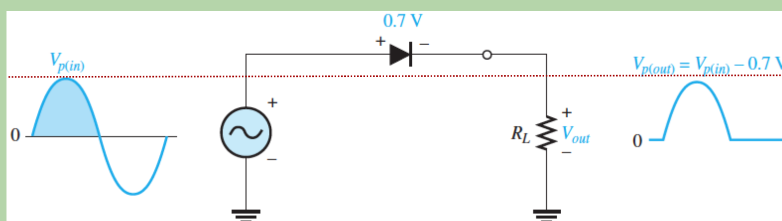
$$V_{AVG} = \frac{V_p}{\pi} = \frac{50\text{ V}}{\pi} = 15.9\text{ V}$$



Effect of the Barrier Potential on the Half-Wave Rectifier Output

- In the previous discussion, the diode was considered ideal.
- Now consider the practical diode model with the barrier potential of 0.7 V taken into account.
- This results in a half-wave output with a peak value (V_p) that is 0.7 V less than the peak value of the input.

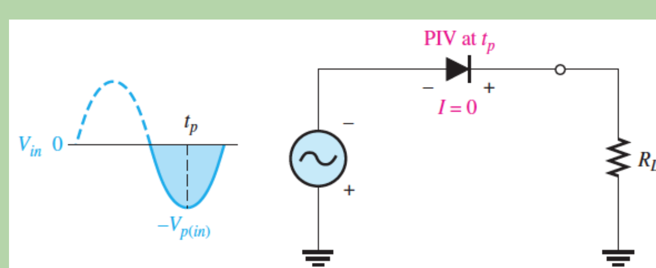
$$V_{p(out)} = V_{p(in)} - 0.7\text{ V}$$



Peak Inverse Voltage (PIV)

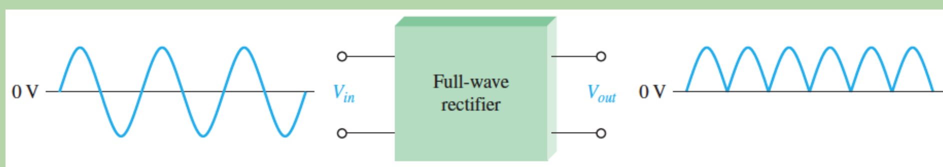
- The **peak inverse voltage (PIV)** equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage.
- A diode should be rated at least 20% higher than the PIV.

$$\text{PIV} = V_{p(in)}$$



Full-wave rectifiers

A **full-wave rectifier** allows unidirectional current through the load during the entire 360° of the input cycle, whereas a half-wave rectifier allows current through the load only during one-half of the cycle. The result of full-wave rectification is an output voltage with a **frequency twice** the input frequency and that pulsates every half-cycle of the input.



The average value (V_{AVG}), which is the value measured on a dc voltmeter, for a full-wave rectified sinusoidal voltage is twice that of the half-wave,

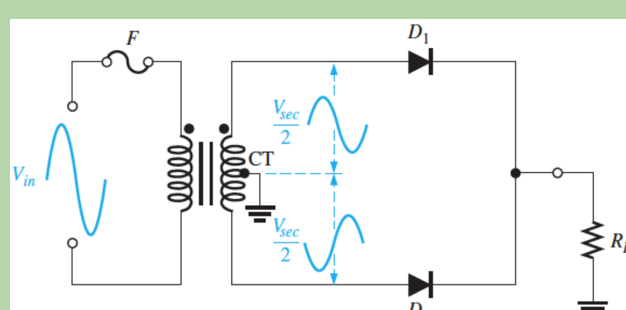
$$V_{AVG} = \frac{2V_p}{\pi}$$

V_{AVG} **is approximately 63.7% of** V_p

Center-Tapped Full-Wave Rectifier Operation

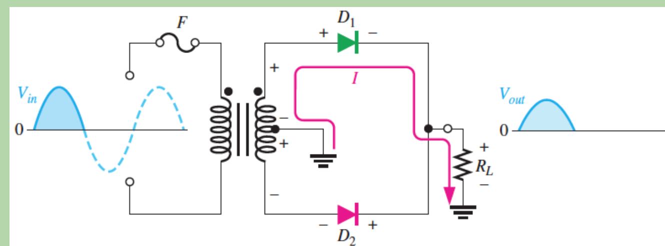
- A **center-tapped rectifier** is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer.
- The ac on each side of the center-tap is 1⁄2 of the total secondary voltage. Only one diode will be biased on at a time.

For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown

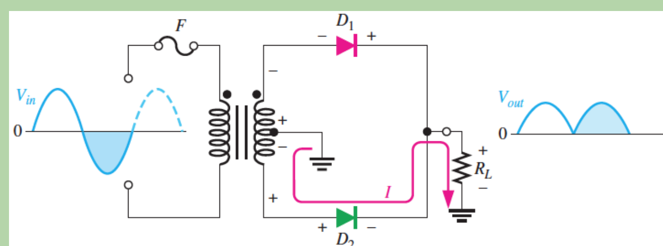


A center-tapped full-wave rectifier.

During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.



During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.



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Effect of the Turns Ratio on the Output Voltage

- The output voltage is determine by the turns ratio, n of the transformer.
- If you do not know the voltage, but do know the turns ratio of the transformer, you can calculate the peak output voltage for a full-wave rectifier from the following equation:

$$V_{p(out)} = \frac{nV_{p(in)}}{2}$$

Where n is the number of turns in the secondary (N_{sec}) divided by the number of turns in the primary (N_{pri})

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Example

Specify the **turns ratio** and **type of transformer** required for a full-wave rectifier if the input voltage is 120 V rms and the required output is 17 V peak?

Solution:

- The input peak voltage is

$$V_{p(in)} = \frac{V_{rms(in)}}{0.707} = \frac{120V}{0.707} = 170V$$

- Rearranging Equation and substituting

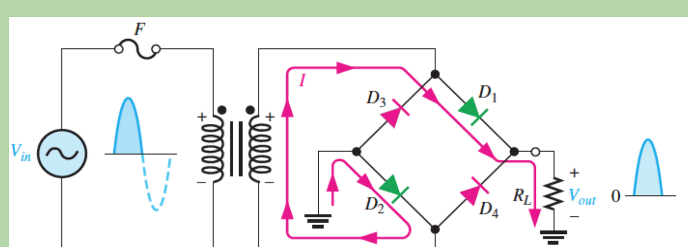
$$V_{p(out)} = \frac{nV_{p(in)}}{2}$$

$$n = \frac{2V_{p(out)}}{V_{p(in)}} = \frac{2(17V)}{170V} = 0.200$$

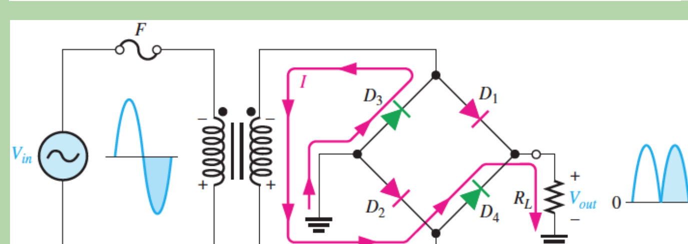
A center-tapped step-down transformer with a turns ration of 0.2 is required.

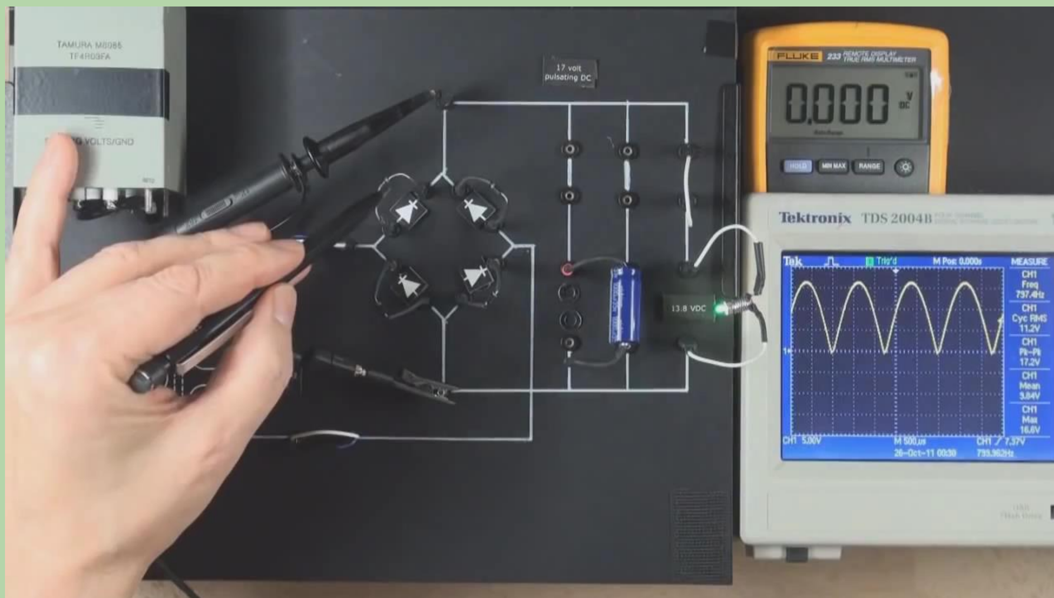
Bridge Full-Wave Rectifier Operation

During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.



During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.





Review Questions

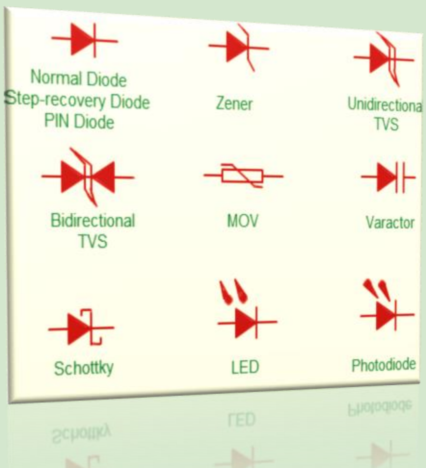
1. At what point on the input cycle does the PIV occur?
2. For a half-wave rectifier, there is current through the load for approximately what percentage of the input cycle?
3. What is the average of a half-wave rectified voltage with a peak value of 10V?
4. What is the peak value of the output voltage of a half-wave rectifier with a peak sine wave input of 25 V?
5. What PIV rating must a diode have to be used in a rectifier with a peak out put voltage of 50 V?
6. How does a full-wave voltage differ from a half-wave voltage?
7. What is the average value of a full-wave rectified voltage with a peak value of 60V?

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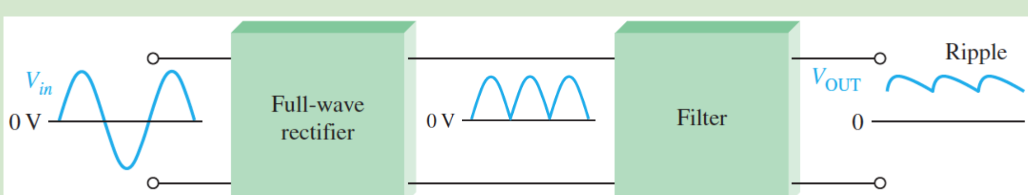
Unit 3: Diodes and Applications

Lecture 10: Power Supply Filters and Special-Purpose Diodes

Dr. Hazem Falah Sakeek
Al-Azhar University of Gaza

Power supply filters

- A power supply filter ideally eliminates the fluctuations in the output voltage of a half-wave or full-wave rectifier and produces a constant-level dc voltage.
- In most power supply applications, the standard (60 Hz or 50 Hz) ac power line voltage must be converted to an approximately constant dc voltage.

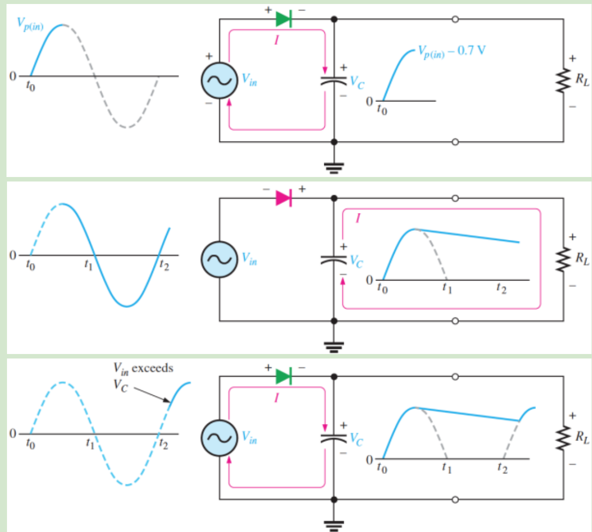


Capacitor-Input Filter

Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.

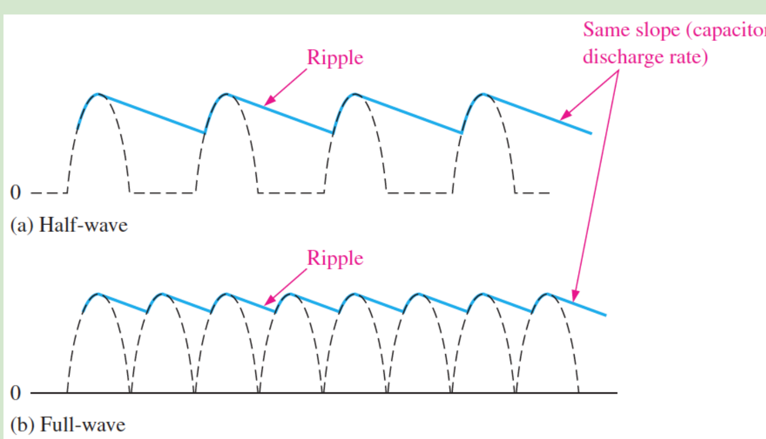
The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased.

The capacitor charges back to peak of input when the diode becomes forward-biased.



Ripple Voltage

Ripple voltage is the variation in the capacitor voltage due to the charging and discharging.



Ripple Factor

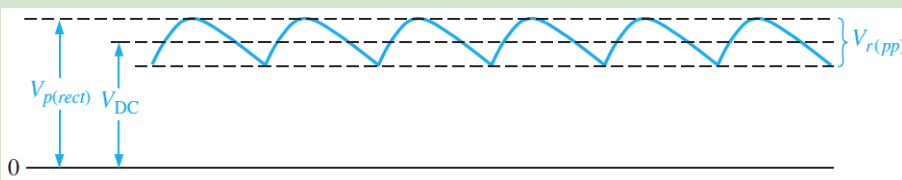
The **ripple factor (*r*)** is an indication of the effectiveness of the filter

$$r = \frac{V_{r(pp)}}{V_{DC}}$$

$V_{r(pp)}$ is the peak-to-peak ripple voltage
V_{DC} is the dc (average) value of the filter's output voltage

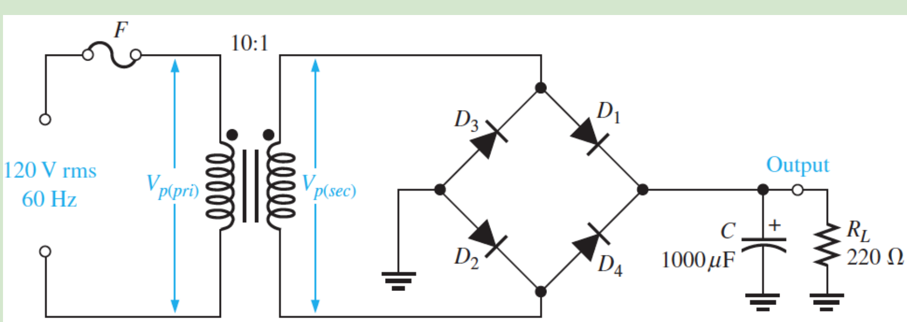
$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} \qquad V_{DC} \cong \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)}$$

When R_L or C increases, the ripple voltage decreases and the dc voltage increases.



Example

Determine the ripple factor for the filtered bridge rectifier with a load as indicated in the Figure



Solution

- **The transformer turns ratio is *n* = 1/10 = 0.1.** The peak primary voltage is

$$V_{p(pri)} = 1.414V_{rms} = 1.414(120\text{ V}) = 170\text{ V}$$

- **The peak secondary voltage is**

$$V_{p(sec)} = nV_{p(pri)} = 0.1(170\text{ V}) = 17.0\text{ V}$$

- **The unfiltered peak full-wave rectified voltage is**

$$V_{p(rect)} = V_{p(sec)} - 1.4\text{ V} = 17.0\text{ V} - 1.4\text{ V} = 15.6\text{ V}$$

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 0.591\text{ V}$$

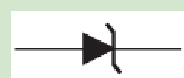
$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = \left(1 - \frac{1}{(240\text{ Hz})(220\ \Omega)(1000\ \mu\text{F})}\right)15.6\text{ V} = 15.3\text{ V}$$

- **The resulting ripple factor is**

$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{0.591\text{ V}}{15.3\text{ V}} = \mathbf{0.039}$$

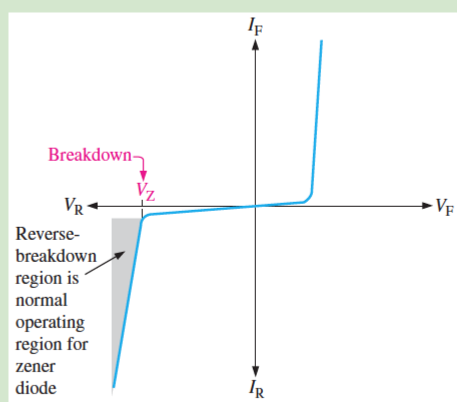
The percent ripple is 3.9%.

The Zener Diodes



A **zener diode** is a silicon *pn* junction device that is designed for operation in the reverse-breakdown region.

The key to zener diode operation is that, when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically.



A major **application** for zener diodes is as a type of **voltage regulator** for providing stable reference voltages for use in power supplies, voltmeters, and other instruments.

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Zener Breakdown

- Two types of reverse breakdown in a zener diode are ***avalanche*** and ***zener***.
- The **avalanche effect**, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage, but zener breakdown occurs in a zener diode at low reverse voltages.

A zener diode is **heavily doped** to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create current.

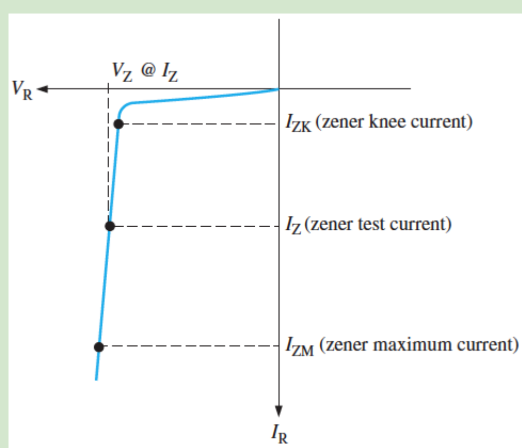
- Zener diodes with breakdown voltages of less than approximately 5V operate predominately in zener breakdown. Those with breakdown voltages greater than approximately 5V operate predominately in **avalanche breakdown.** Both types, however, are called *zener diodes.*

Zener Breakdown Characteristics

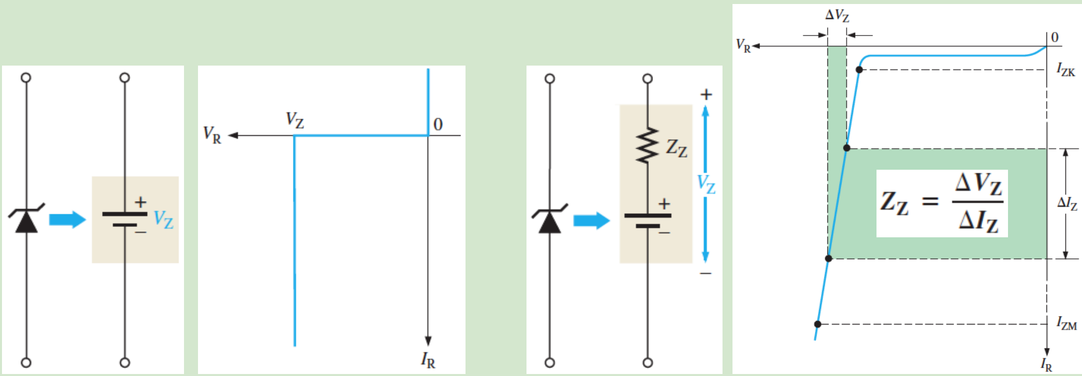
The reverse voltage (V_R) is increased, the reverse current (I_R) remains extremely small up to the "knee" of the curve.

The reverse current is also called the zener current, I_Z. At this point, the internal zener resistance, also called zener impedance (Z_Z), begins to decrease as the reverse current increases rapidly.

From the bottom of the knee, the zener breakdown voltage (V_Z) remains essentially constant



Zener Equivalent Circuits

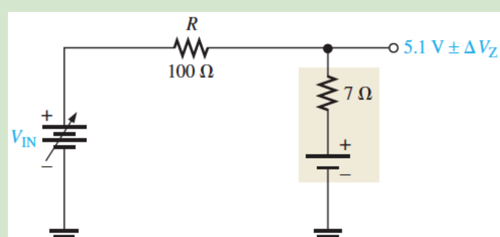


Ideal model *Characteristic curve* *Practical model* *Characteristic curve*

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Example

Determine the minimum and the maximum input voltages that can be regulated by the zener diode. (V_Z = 5.1 V at I_Z = 49 mA, I_{ZK} = 1 mA, and Z_Z = 7 Ω at I_Z and assume Zz is constant over the range of current values, and the power dissipation is 1 W).



Solution:

At I_{ZK} = 1 mA, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} - \Delta V_Z = 5.1\text{ V} - (I_Z - I_{ZK})Z_Z$$
$$= 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$$
$$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$$

Therefore

$$V_{IN(min)} = I_{ZK}R + V_{OUT} = (1\text{ mA})(100\ \Omega) + 4.76\text{ V} = \mathbf{4.86\text{ V}}$$

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To find the maximum input voltage,

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\ W}{5.1\ V} = 196\ mA$$

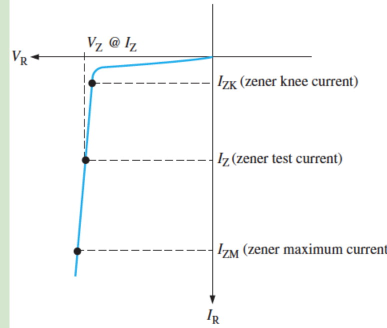
At I_{ZM}, the output voltage is

$$V_{OUT} \cong 5.1\ V + \Delta V_Z = 5.1\ V + (I_{ZM} - I_Z)Z_Z$$

$$= 5.1\ V + (147\ mA)(7\ \Omega) = 5.1\ V + 1.03\ V = 6.13\ V$$

Therefore,

$$V_{IN(max)} = I_{ZM}R + V_{OUT} = (196\ mA)(100\ \Omega) + 6.13\ V = \mathbf{25.7\ V}$$

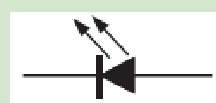


This shows that this zener diode can ideally regulate an input voltage from 4.84V to 25.7V and maintain an approximate 5.1V output.

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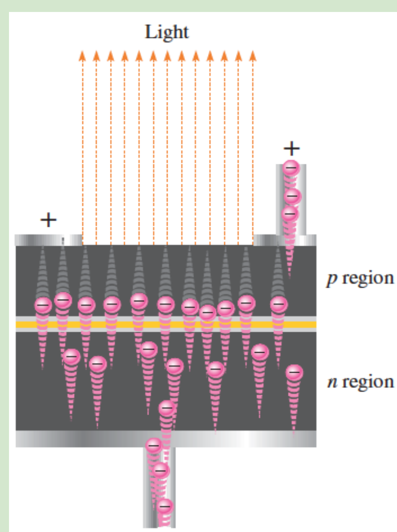
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The Light-Emitting Diode (LED)



The basic operation of an LED (light-emitting diode) is as follows:

- When the device is **forward biased**, electrons cross the pn junction from the n-type material and recombine with holes in the p-type material.
- When recombination takes place, the recombining electrons release energy in the form of heat and **light**.

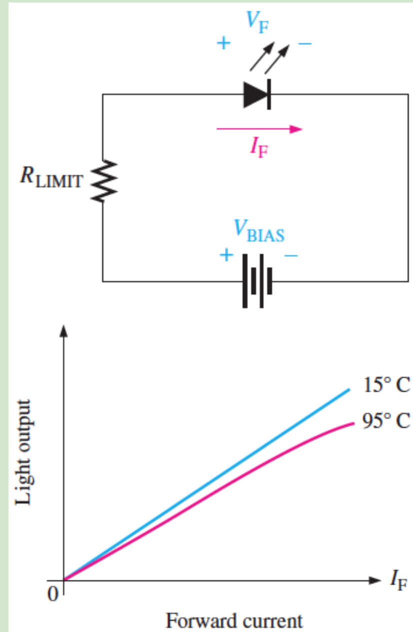


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LED Biasing

- The amount of power output translated into light is directly proportional to the forward current.
- An increase in I_F corresponds proportionally to an increase in light output.
- The light output (both intensity and color) is also dependent on temperature. Light intensity goes down with higher temperature as indicated in the figure.

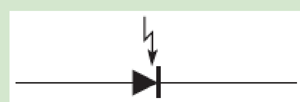


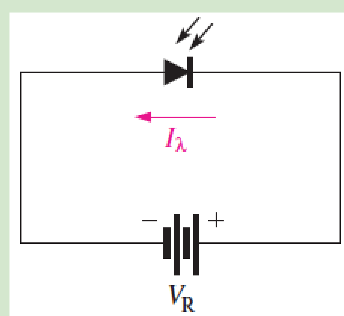
The Photodiode

The **photodiode** is a device that operates in reverse bias, where I_λ is the reverse light current. The photodiode has a small transparent window that allows light to strike the *pn* junction.

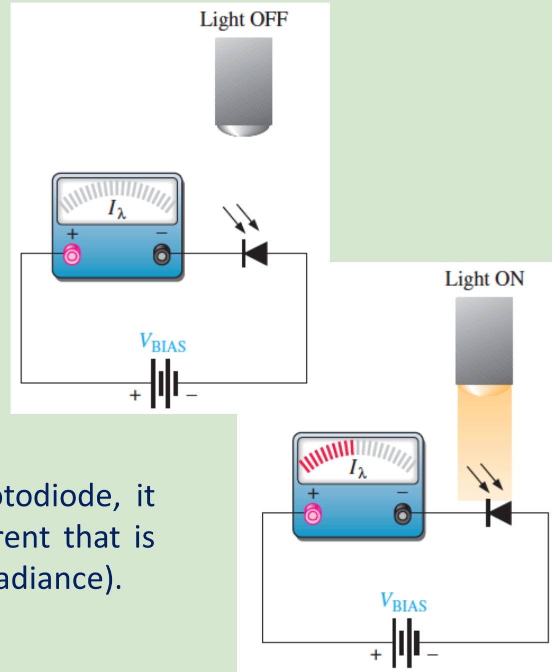
A photodiode differs from a rectifier diode in that when its *pn* junction is exposed to light, the reverse current increases with the light intensity. When there is no incident light, the reverse current, I_λ, is almost negligible and is called the **dark current**.

An increase in the amount of light intensity, expressed as irradiance (mW/cm^2), produces an increase in the reverse current





The photodiode allows essentially no reverse current (except for a very small dark current) when there is no incident light.



When a light beam strikes the photodiode, it conducts an amount of reverse current that is proportional to the light intensity (irradiance).

Self-test

Try to solve the Self-test in your text book

Electronic Devices

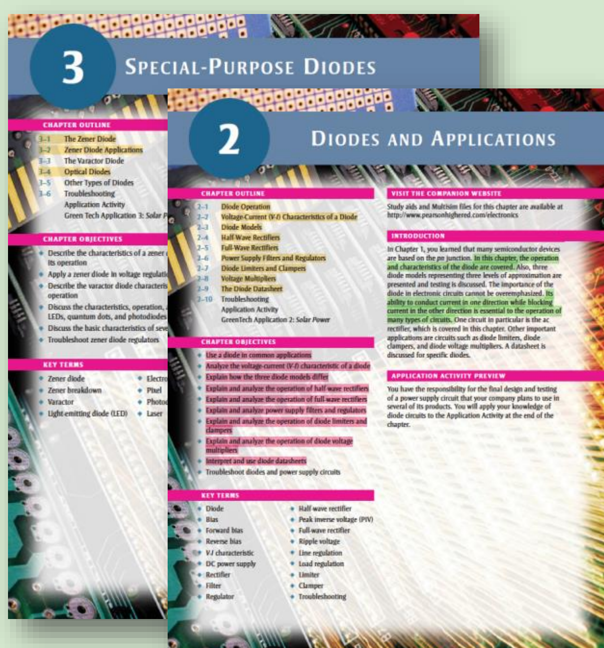
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Electronic Fundamentals

Circuits, Devices, and Applications



Unit 3: Diodes and Applications

Lecture 11: Discussion for Unit 2 & 3

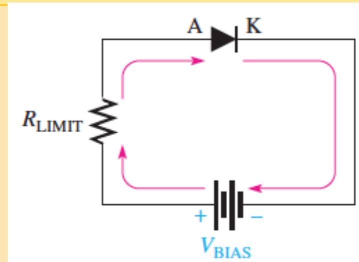
Part (1)

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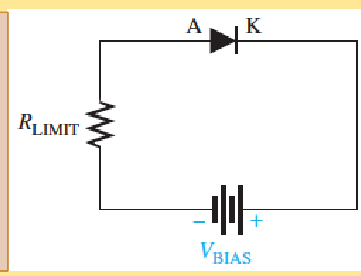
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Summary of Diode

- The bias voltage must be greater than the barrier potential.
- Barrier potential: 0.7 V for silicon.
- Majority carriers provide the forward current.
- The depletion region narrows.



- The bias voltage must be less than the breakdown voltage.
- There is no majority carrier current after transition time.
- Minority carriers provide a negligibly small reverse current.
- The depletion region widens.

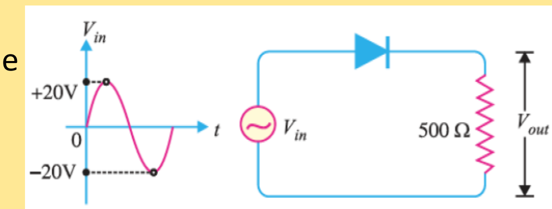


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Example 1

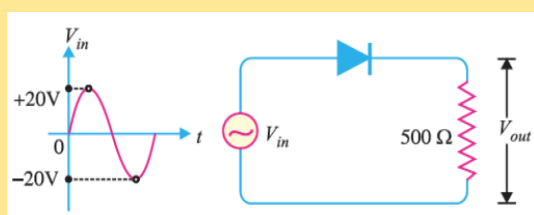
An ac voltage of peak value 20 V is connected in series with a silicon diode and load resistance of 500 Ω. If the forward resistance of the diode is 10 Ω, find:

- (a) peak current through the diode
- (b) peak output voltage.



What will be these values if the diode is considered as an ideal diode?

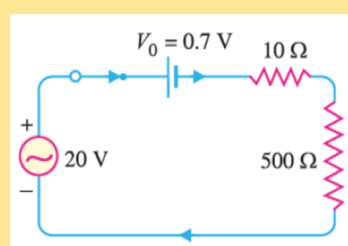
Solution. The diode will conduct during the positive half-cycles of ac input voltage. The equivalent circuit is



(a) peak current through the diode

$V_F = V_{PB} + (I_f)_{peak}\,[r_f + R_L]$

$(I_f)_{peak} = \frac{V_F - V_{PB}}{r_f + R_L} = \frac{20-0.7}{10+500} = 37.8 \text{ mA}$



(b) peak output voltage

$V_{out} = (I_f)_{peak} \times R_L = 37.8\times10^{-3}\text{A} \times 500\ \Omega = 18.9\text{ V}$

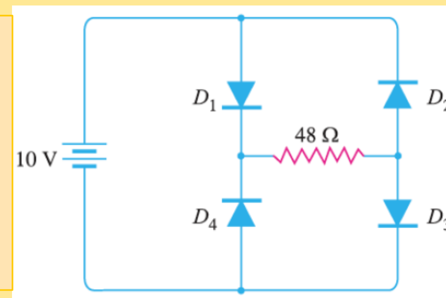
For an ideal diode $V_{PB} = 0$ and $r_f = 0$

$(I_f)_{peak} = \frac{V_F}{R_L} = \frac{20}{500} = 40 \text{ mA}$ & $V_{out} = (I_f)_{peak} \times R_L = 40\times10^{-3}\text{ A} \times 500\ \Omega = 20\text{ V}$

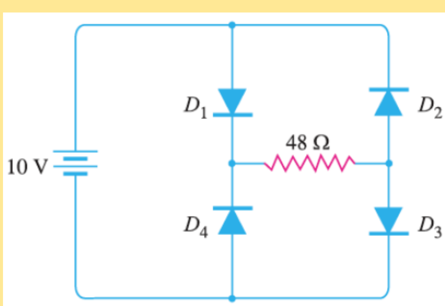
Example 2

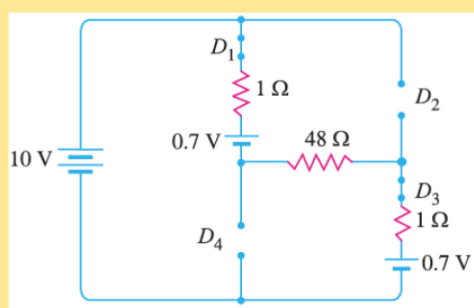
Calculate the current through 48 Ω resistor in the circuit shown in the Figure (i). Assume the diodes to be of silicon and forward resistance of each diode is 1 Ω.

Diodes D_1 and D_3 are forward biased while diodes D_2 and D_4 are reverse biased. We can, therefore, consider the branches containing diodes D_2 and D_4 as "open".
Replacing diodes D_1 and D_3 by their equivalent circuits and making the branches containing diodes D_2 and D_4 open,



We get the circuit shown in the Figure. Note that for a silicon diode, the barrier voltage is 0.7 V.

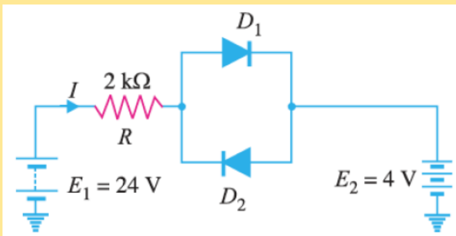


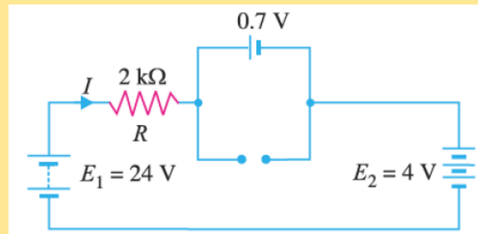


Net circuit voltage = 10 − 0.7 − 0.7 = 8.6 V
Total circuit resistance = 1 + 48 + 1 = 50 Ω
Circuit current = 8.6/50 = 0.172 A = **172 mA**

Example 3

Determine the current I in the circuit shown in the Figure. Assume the diodes to be of silicon and forward resistance of diodes to be zero.



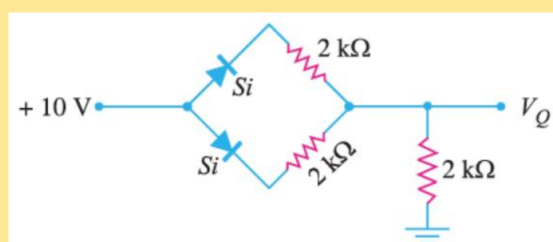


Solution. The conditions of the problem suggest that diode D_1 is forward biased and diode D_2 is reverse biased. We can, therefore, consider the branch containing diode D_2 as open. Further, diode D_1 can be replaced by its simplified equivalent circuit.

$$I = \frac{E_1 - E_2 - V_0}{R} = \frac{24 - 4 - 0.7}{2\ \text{k}\Omega} = \frac{19.3\ \text{V}}{2\ \text{k}\Omega} = \mathbf{9.65\ mA}$$

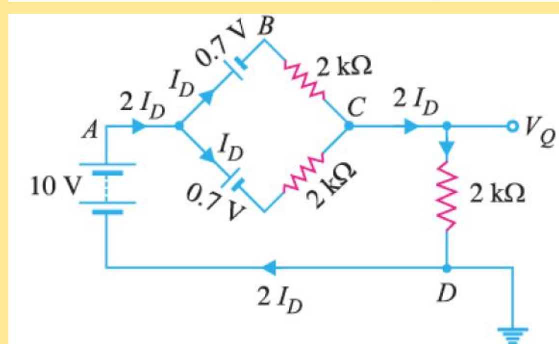
Example 4

Find V_Q and I_D in the network shown. Use practical model.



Solution. By symmetry, current in each branch is I_D so that current in branch *CD* is $2I_D$.

Applying Kirchhoff's voltage law to the closed circuit *ABCDA*, we have,



$$-0.7 - I_D \times 2 - 2I_D \times 2 + 10 = 0$$

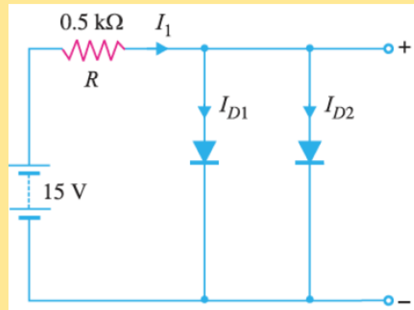
$$6I_D = 9.3$$

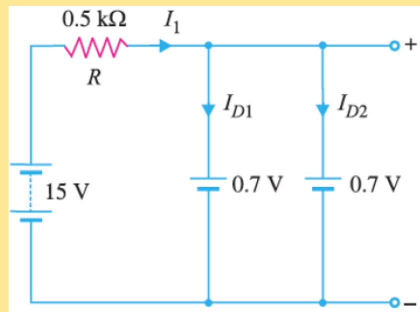
$$I_D = \frac{9.3}{6} = \mathbf{1.55\ mA}$$

$$V_Q = (2I_D) \times 2\ \text{k}\Omega = (2 \times 1.55\ \text{mA}) \times 2\ \text{k}\Omega = \mathbf{6.2\ V}$$

Example 5

Determine current through each diode in the circuit shown. Use practical model. Assume diodes to be similar.





Solution. The applied voltage forward biases each diode so that they conduct current in the same direction.

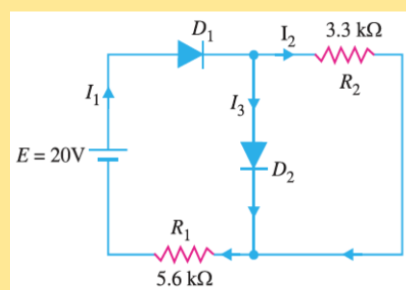
$$I_1 = \frac{\text{Voltage across } R}{R} = \frac{15 - 0.7}{0.5\ \text{k}\Omega} = 28.6\ \text{mA}$$

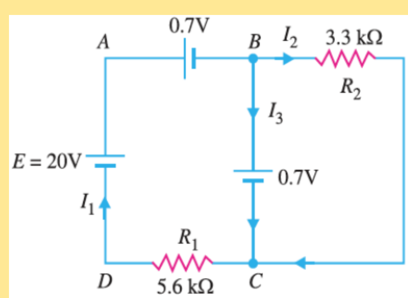
Since the diodes are similar

$$I_{D1} = I_{D2} = \frac{I_1}{2} = \frac{28.6}{2} = \mathbf{14.3\ mA}$$

Example 6

Determine the currents I_1, I_2 and I_3 for the network shown. Use practical model for the diodes.





Solution. An inspection of the circuit shown it shows that both diodes D_1 and D_2 are forward biased.

The voltage across R_2 (= 3.3 k Ω) is 0.7V.

$$\therefore \qquad I_2 = \frac{0.7\ \text{V}}{3.3\ \text{k}\Omega} = \mathbf{0.212\ mA}$$

Applying Kirchhoff's voltage law to loop *ABCDA*, we have, $-0.7 - 0.7 - I_1 R_1 + 20 = 0$

$$I_1 = \frac{20 - 0.7 - 0.7}{R_1} = \frac{18.6\ \text{V}}{5.6\ \text{k}\Omega} = \mathbf{3.32\ mA}$$

$$I_3 = I_1 - I_2 = 3.32 - 0.212 = \mathbf{3.108\ mA}$$

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Electronic Fundamentals

Circuits, Devices, and Applications

Unit 3: Diodes and Applications

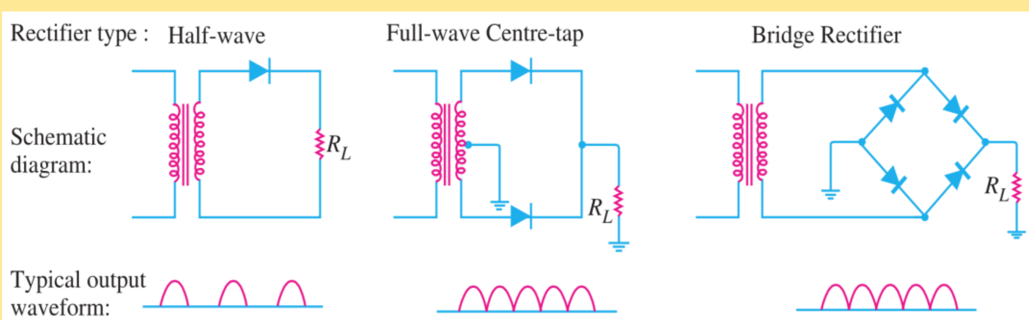
Lecture 12: Discussion for Unit 2 & 3

Part (2)

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Summary of power supply rectifiers



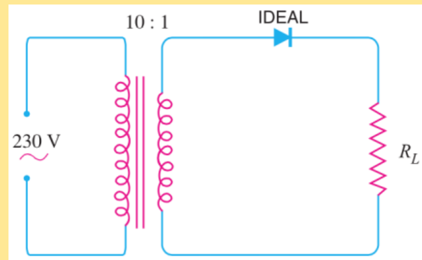
S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	no	yes	no
3	Max. efficiency	40.6%	81.2%	81.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	f_{in}	$2 f_{in}$	$2 f_{in}$
6	Peak inverse voltage	V_m	$2 V_m$	V_m

Example 1

An ac supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10:1. Assume the diode to be ideal. Find

(i) the output dc voltage

(ii) the peak inverse voltage.



Solution

Primary to secondary turns is $N_1/N_2 = 10$

rms of the primary voltage = 230 V

∴ Max primary voltage $V_{pm} = \sqrt{2} \times 230 = 325.3$ V

∴ Max secondary voltage $V_{sm} = V_{pm} \times (N_2/N_1) = 325.3 \times (1/10) = 32.53$ V

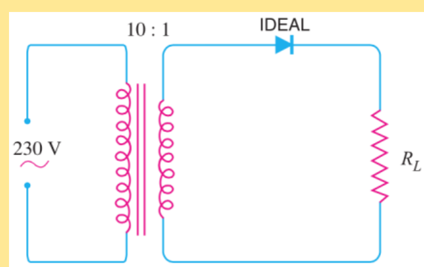
(i) the output dc voltage

$$I_{d.c.} = \frac{I_m}{\pi}$$

$$V_{dc} = \frac{I_m}{\pi} \times R_L$$

$$= \frac{V_{sm}}{\pi}$$

$$= \frac{32.53}{\pi} = \mathbf{10.36\ V}$$



(ii) the peak inverse voltage.

- The maximum secondary voltage appears across the diode.
- ∴ Peak inverse voltage V_{sm} = **32.53 V**

Example 2

A half-wave rectifier is used to supply 50V dc to a resistive load of 800 Ω. The diode has a resistance of 25 Ω. **Calculate ac voltage required.**

Solution

Output dc voltage, V_{dc} = 50 V

Diode resistance, r_f = 25 Ω

Load resistance, R_L = 800 Ω

Let V_m be the maximum value of ac voltage required.

$$\therefore V_{dc} = I_{dc} \times R_L$$

$$V_{dc} = \frac{I_m}{\pi} \times R_L$$

$$\left[\because I_m = \frac{V_m}{r_f + R_L}\right]$$

$$V_{dc} = \frac{V_m}{\pi(r_f + R_L)} \times R_L$$

$$50 = \frac{V_m}{\pi(25 + 800)} \times 800$$

$$V_m = \frac{\pi \times 825 \times 50}{800} = \mathbf{162\ V}$$

Hence, ac voltage of maximum value 162 V is required.

Example 3

A full-wave rectifier uses two diodes, the internal resistance of each diode may be assumed constant at 20 Ω. The transformer rms secondary voltage from center tap to each end of secondary is 50 V and load resistance is 980 Ω. Find: (i) *the average load current,* (*ii*) *the rms value of load current*

Solution

Max. ac voltage $V_m = 50 \times \sqrt{2} = 70.7\ \text{V}$

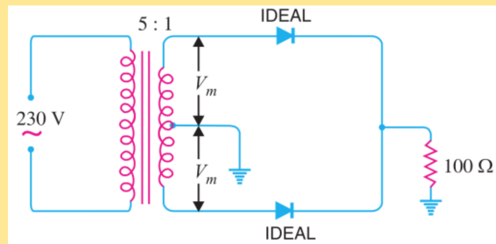
Max. load current $I_m = \frac{V_m}{r_f + R_L} = \frac{70.7\ \text{V}}{(20 + 980)\ \Omega} = 70.7\ \text{mA}$

(*i*) *average* load current $I_{dc} = \frac{2I_m}{\pi} = \frac{2 \times 70.7}{\pi} = \mathbf{45\ mA}$

(ii) RMS value of load current is $I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}} \overrightarrow{AB} = \mathbf{50\ mA}$

Example 4

In the center-tap circuit shown, the diodes are assumed to be ideal i.e. having zero internal resistance. Find: (i) dc output voltage (ii) peak inverse voltage.



Solution

Primary to secondary turns, $N_1/N_2 = 5$

RMS primary voltage = 230 V

∴ RMS secondary voltage = 230×(1/5) = 46V

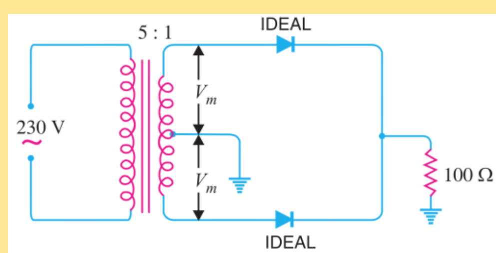
Maximum voltage across secondary = 46 x $\sqrt{2}$ = 65V

Maximum voltage across half secondary winding is V_m =65/2 = 32.5V

(i) dc output voltage

$$V_{AVG} = \frac{2V_m}{\pi}$$

$V_{dc} = V_{AVG}$= 2 x 32.5 / 3.14 = **20.7V**



(ii) peak inverse voltage.

The peak inverse voltage is equal to maximum secondary voltage, *i.e*.

PIV = **65 V**

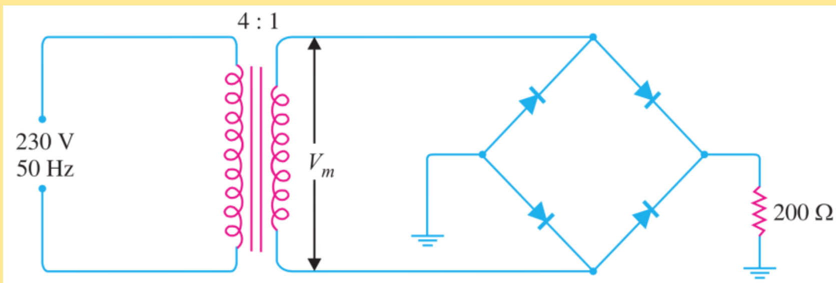
Example 5

In the bridge type circuit shown, the diodes are assumed to be ideal. Assume primary to secondary turns to be 4. Find:

(i) dc output voltage

(ii) peak inverse voltage

(iii) output frequency.



Solution

Primary/secondary turns, $N_1/N_2 = 4$

RMS primary voltage = 230 V

∴ RMS secondary voltage = 230 (N_2/N_1) = 230 × (1/4) = 57.5 V

Maximum voltage across secondary is

$V_m = 57.5 \times \sqrt{2} = 81.3V$

Average output voltage, $V_{AVG} = \frac{2V_m}{\pi}$

(i) ∴ dc output voltage, $V_{dc} = V_{AVG} = 2 \times 81.3 / 3.14 =$ **52V**

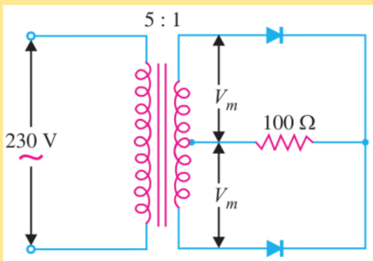
(ii) peak inverse voltage (*PIV* = **81.3V**)

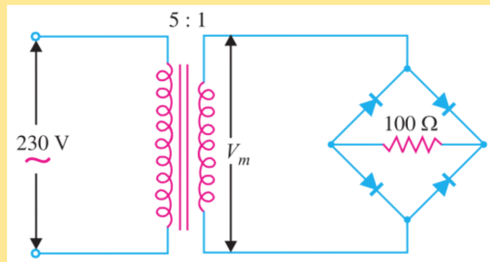
(iii) In full wave rectification, there are two output pulses for each complete cycle of the input ac voltage. Therefore, the output frequency is twice that of the ac supply frequency *i.e.*

$$f_{out} = 2 \times f_{in} = 2 \times 50 = \mathbf{100Hz}$$

More problem to be solved by your self

(1) Figures show the center-tap and bridge type circuits having the same load resistance and transformer turn ratio. The primary of each is connected to 230 V, 50 Hz supply. Assume the diodes to be ideal. (i) Find the dc voltage in each case. (ii) PIV for each case for the same dc output.





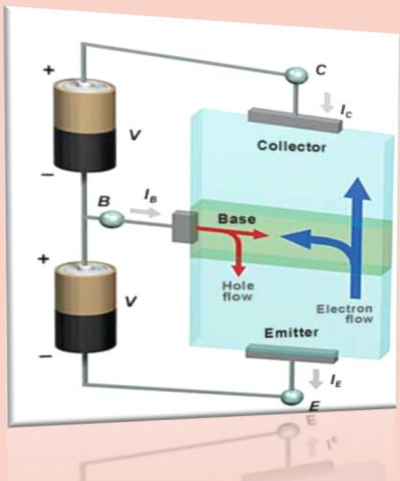
(2) The four diodes used in a bridge rectifier circuit have forward resistances which may be considered constant at 1Ω and infinite reverse resistance. The alternating supply voltage is 240 V rms and load resistance is 480 Ω. Calculate (i) average load current and (ii) power dissipated in each diode.

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Electronic Fundamentals

Circuits, Devices, and Applications

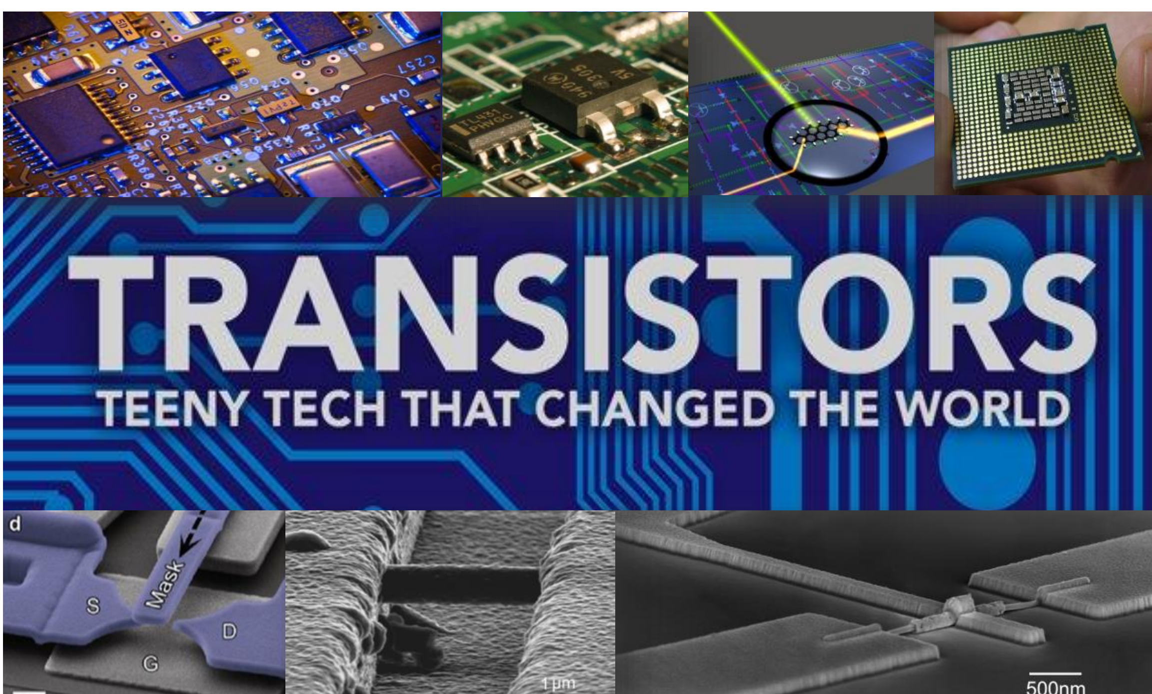


Unit 4: Bipolar Junction Transistors (BJT)

Lecture 13: BJT Operation

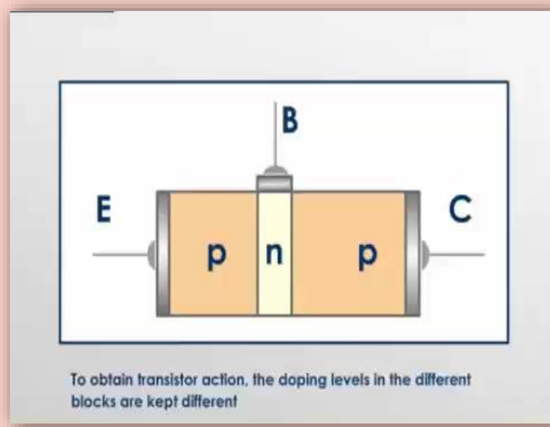
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Unit 4: Bipolar Junction Transistors (BJT)

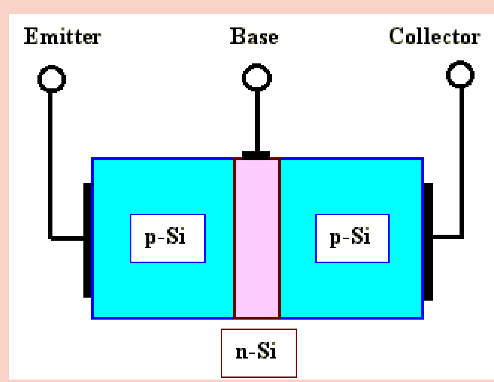
- Transistor construction
- Transistor operation
- Transistor amplifying action
- BJT Characteristics and Parameters
- Transistor connections and characteristics
  - Common Base Connection
  - Common Emitter configuration
  - common collector connection



3

Introduction

- When a third doped element is added to a crystal diode in such a way that two *pn* junctions are formed, the resulting device is known as a *transistor*.
- The transistor—an entirely new type of electronic device—is capable of achieving amplification of weak signals.
- Transistors are mechanically strong, have practically unlimited life and can do some jobs better than vacuum tubes.

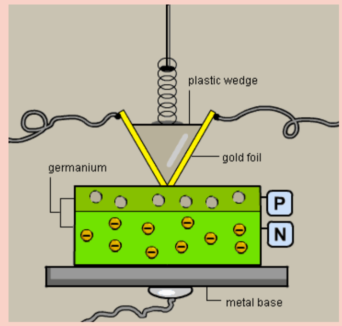


Junction Transistor

4

The First Transistor: Point-contact transistor





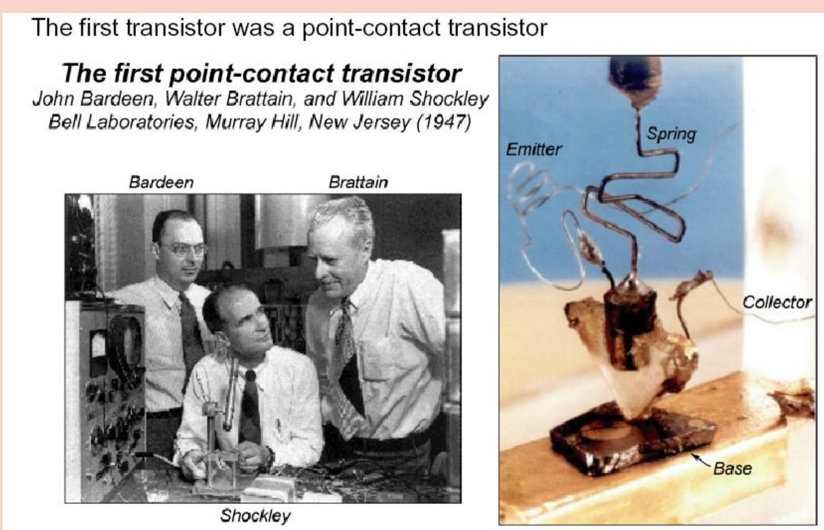
A point-contact transistor was the first type of solid state electronic transistor ever constructed.

It was made by researchers John Bardeen & Walter Houser Brattain at Bell Laboratories in December 1947.

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Point-Contact Transistor – first transistor ever made



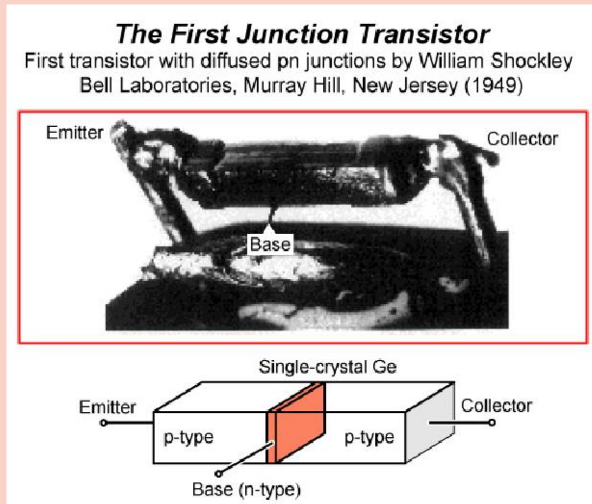
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First Bipolar Junction Transistors

W. Shockley invented the p-n junction transistor

The physically relevant region is moved to the bulk of the material

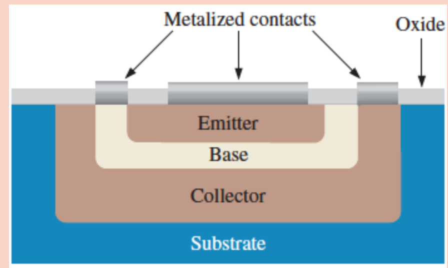


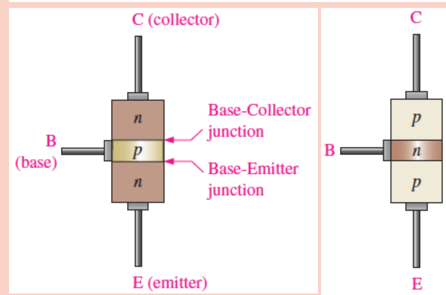
The Junction Transistor

- Initially known simply as the **junction transistor**.
- It did not become practical until the early 1950s.
- The term "**bipolar**" was tagged onto the name to distinguish the fact that both carrier types play important roles in the operation.
- **Field Effect Transistors** (**FET**s) are "**unipolar**" transistors since their operation depends primarily on a single carrier type.

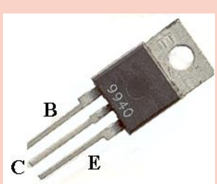
Bipolar Junction Transistor (BJT) structure

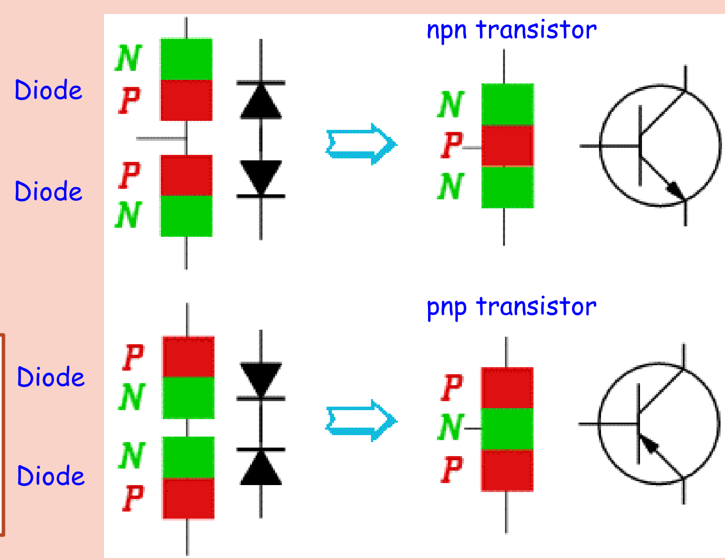
- The **BJT** is constructed with three doped semiconductor regions separated by two *pn* junctions.
- The three regions are called **emitter**, **base**, and **collector**.
- **One type** consists of two *n* regions separated by a *p* region (*npn*), and **the other type** consists of two *p* regions separated by an *n* region (*pnp*).
- The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions.





Basic models of BJT

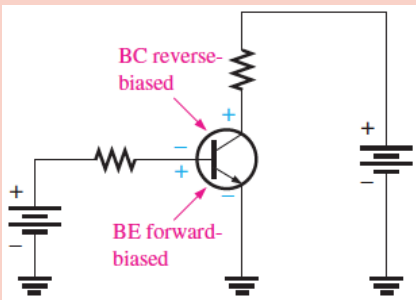




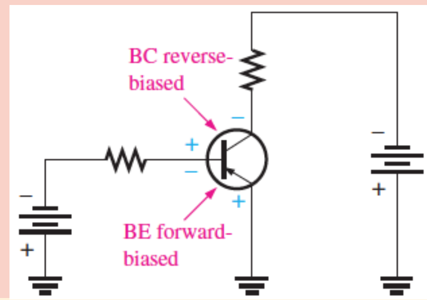
Note that emitter is shown by an arrow which indicates the direction of conventional current flow with forward bias.

Basic BJT operation (Bias)

In order for a BJT to operate properly as an **amplifier**, the two *pn* junctions must be correctly biased with external dc voltages.



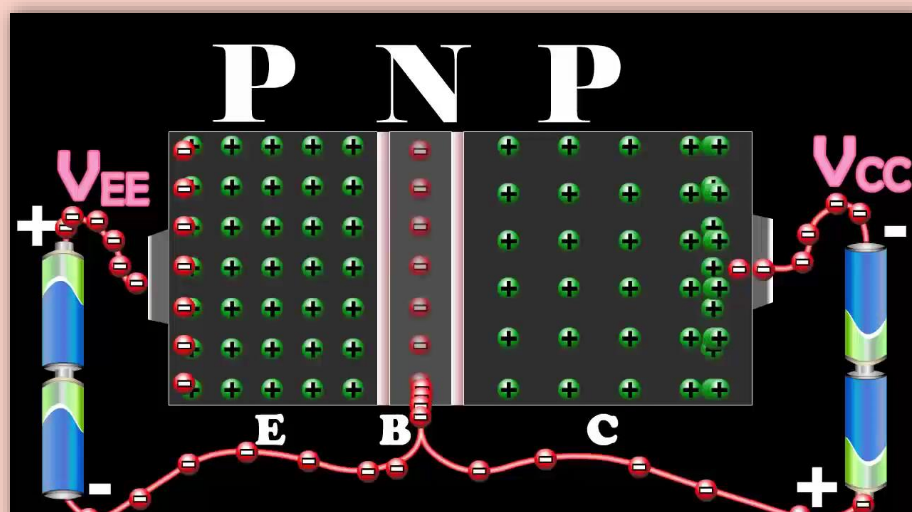
Forward-reverse bias of a BJT



The bias arrangement for both *npn* and *pnp* BJTs for operation as an **amplifier.**

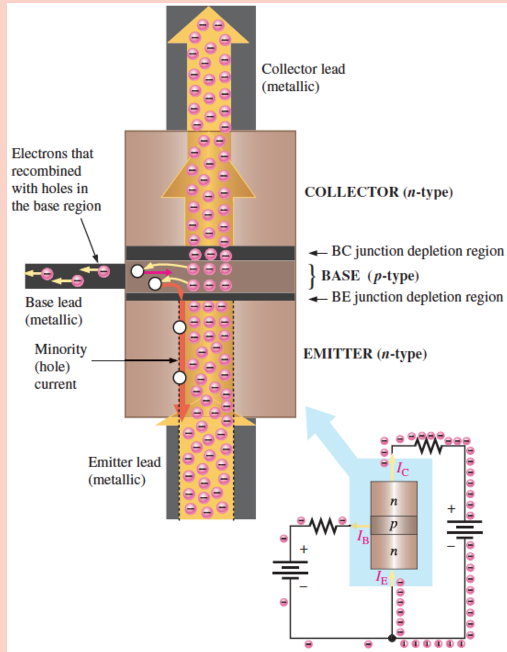
Notice that in both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased with external dc voltages.

Inside the *pnp* structure

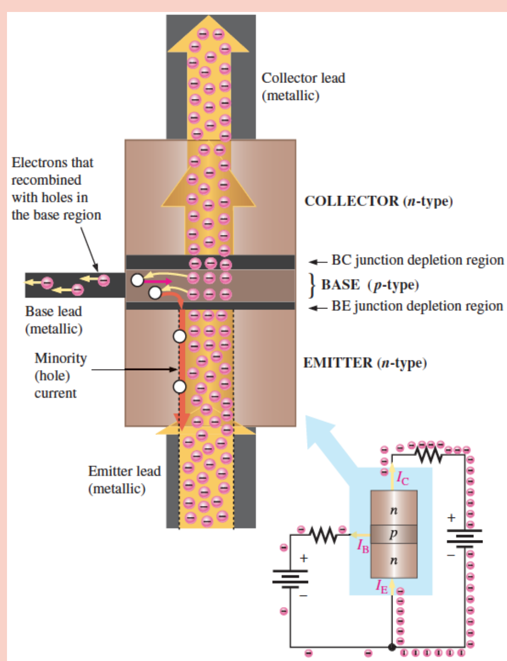


Inside the *npn* structure

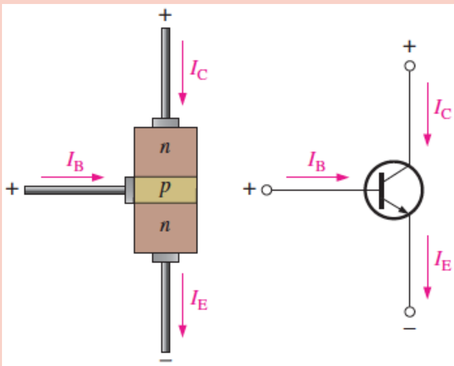
- The heavily doped *n*-type emitter region has a very high density of conduction-band (free) electrons,
- These free electrons easily diffuse through the forward- based BE junction into the lightly doped and very thin *p*-type base region.
- A small percentage of the total number of free electrons injected into the base region recombine with holes and move as valence electrons through the base region and into the emitter region as hole current.

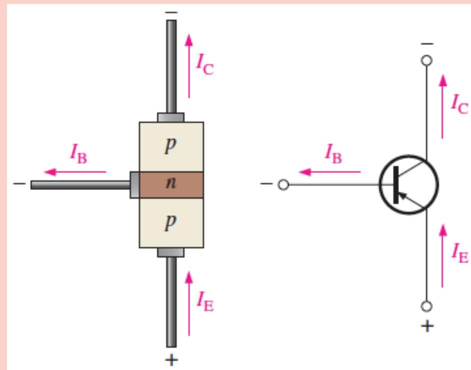


- Most of the free electrons that have entered the base do not recombine with holes because the base is very thin.
- As the free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage.
- The emitter current is slightly greater than the collector current because of the small base current that splits off from the total current injected into the base region from the emitter.



Transistor Currents





The emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows

$$I_E = I_B + I_C$$

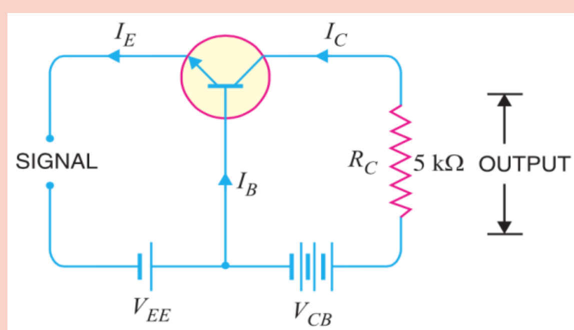
Transistor Circuit as an Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier.

The weak signal is applied between emitter-base junction and output is taken across the load R_C connected in the collector circuit.

In order to achieve amplification, the input circuit should always remain forward biased.

A dc voltage (bias voltage) V_{EE} is applied in the input circuit in addition to the signal.



The basic circuit of a transistor amplifier

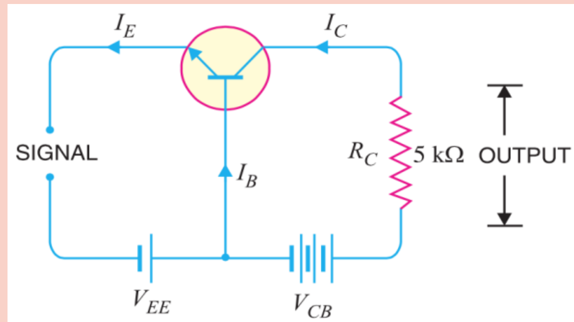
As the input circuit has low resistance, therefore, a small change in signal voltage causes an appreciable change in emitter current.

This causes almost the same change in collector current due to transistor action.

The collector current flowing through a high load resistance R_C produces a large voltage across it.

Thus, a weak signal applied in the input circuit appears in the amplified form in the collector circuit.

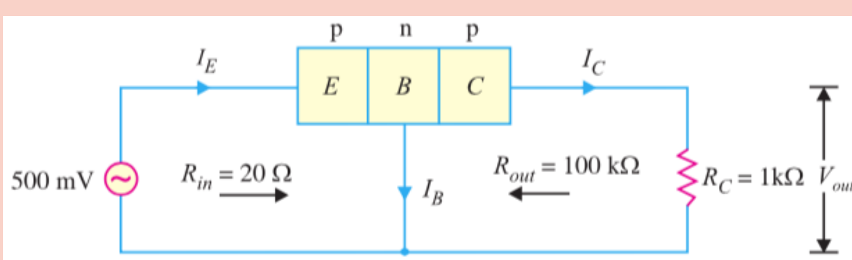
It is in this way that a transistor acts as an amplifier.



The basic circuit of a transistor amplifier

Example 1

A common base transistor amplifier has an input resistance of 20 Ω and output resistance of 100 kΩ. The collector load is 1 kΩ. If a signal of 500 mV is applied between emitter and base, find the voltage amplification. Assume I_B is very small.



Solution

Input current: $I_E = \frac{\text{Signal}}{R_{in}} = \frac{500\text{ mV}}{20\ \Omega} = 25\text{ mA}.$

$I_E = I_C$ (since I_B very small and it can be neglected).

Output voltage: $V_{out} = I_C R_C = 25\text{ mA} \times 1\text{ k}\Omega = 25\text{ V}$

Voltage amplification: $A_v = \frac{V_{out}}{\text{signal}} = \frac{25\,V}{500\,mV} = 50$

Note: the basic amplifying action is produced by transferring a current from a *low-resistance* to a *high-resistance* circuit. Consequently, the name transistor is given to the device by combining:

Transfer + Resistor = Transistor

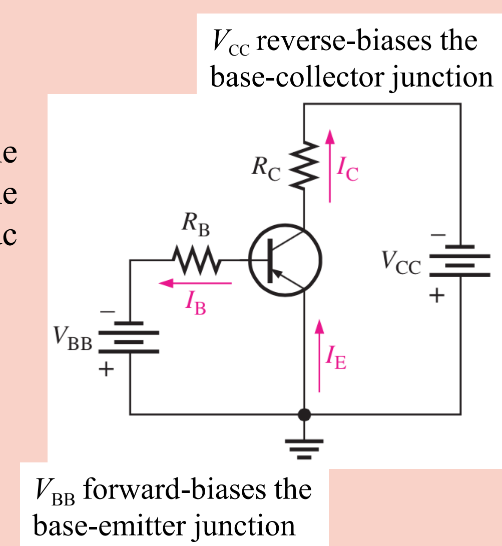
DC Beta (β_{DC}) and DC Alpha (α_{DC})

DC Beta (β_{DC})

The dc current **gain** of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc beta (β_{DC}).

$$\beta_{DC} = \frac{I_C}{I_B}$$

Typical values of β_{DC} range from less than 20 to 200 or higher.



DC Alpha (α_{DC})

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc alpha $\boldsymbol{\alpha_{DC}}$

$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typically, values of $\boldsymbol{\alpha_{DC}}$ range from 0.95 to 0.99 or greater, but $\boldsymbol{\alpha_{DC}}$ is always less than 1.

The reason is that I_C is always slightly less than I_E by the amount of I_B.

The alpha is a less-used parameter than beta in transistor circuits.

Example

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where I_B = 50 μA and I_C = 3.65 mA.

Solution:

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\ mA}$$

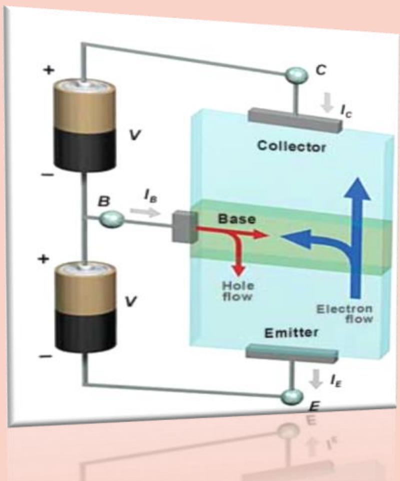
Next.....

Transistor Connections

- **(*i*) common base connection**
- **(*ii*) common emitter connection**
- **(*iii*) common collector connection**

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Electronic Fundamentals

Circuits, Devices, and Applications

Unit 4: Bipolar Junction Transistors (BJT)

Lecture 14: Transistor Connections

Common Base Connection

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Unit 4: Bipolar Junction Transistors (BJT)

- Transistor construction
- Transistor operation
- Transistor amplifying action
- BJT Characteristics and Parameters
- Transistor connections and characteristics
  - Common Base Connection
  - Common Emitter configuration
  - common collector connection



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Transistor Connections

- There are three leads in a transistor, emitter, base and collector terminals.
- When a transistor is to be connected in a circuit, we require four terminals; two for the input and two for the output.
- This difficulty is overcome by making one terminal of the transistor common to both input and output terminals.

The transistor can be connected in a circuit in the following three ways:

(i) common base connection

(ii) common emitter connection

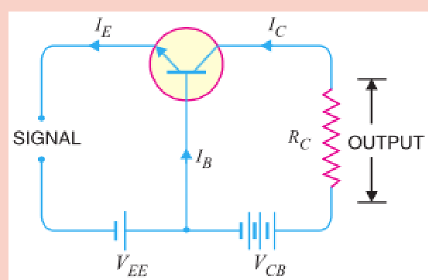
(iii) common collector connection

Note: The emitter is always biased in the forward direction, while the collector always has a reverse bias.

Common Base Connection

Current amplification factor (α).

It is the ratio of output current to input current. In a common base connection, the input current is the emitter current I_E and output current is the collector current I_C.



Definition of α.

The ratio of change in collector current to the change in emitter current at constant collector- base voltage V_{CB}

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \text{at constant } V_{CB}$$

It is clear that current amplification factor is less than unity (range from 0.9 to 0.99).

Expression for collector current: total collector current consists of:

(*i*) That part of emitter current which reaches the collector terminal *i.e.* αI_E.

(*ii*) The leakage current $I_{leakage}$. This current is due to the movement of minority carriers across base-collector junction on account of it being reverse biased. This is generally much smaller than αI_E.

Total collector current, $I_C = \alpha I_E + I_{leakage}$

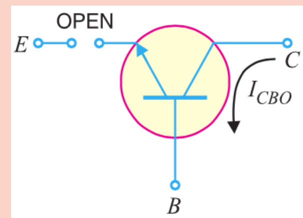
$$I_C = \alpha I_E + I_{CBO}$$

$$I_E = I_C + I_B$$

$$I_C = \alpha (I_C + I_B) + I_{CBO}$$

$$I_C (1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$$



I_{CBO}, is the collector-base current with emitter open

The collector current of a transistor can be controlled by either the emitter or base current.

Example 1

In a common base connection, I_C = 0.95 mA and I_B = 0.05 mA. Find the value of α.

Solution

From

$$I_E = I_B + I_C = 0.05 + 0.95 = 1 \text{ mA}$$

Current amplification factor

$$\alpha = \frac{I_C}{I_E} = \frac{0.95}{1} = \mathbf{0.95}$$

Example 2

In a common base connection, the emitter current is 1mA. If the emitter circuit is open, the collector current is 50 μA. Find the total collector current. Given that α = 0.92.

Solution

We have

$$I_E = 1 \text{ mA}, \alpha = 0.92, \quad I_{CBO} = 50 \ \mu\text{A}$$

Total collector current

$$I_C = \alpha I_E + I_{CBO} = 0.92 \times 1 + 50 \times 10^{-3}$$

$$= 0.92 + 0.05 = \mathbf{0.97 \text{ mA}}$$

Example 3

In a common base connection, α = 0.95. The voltage drop across 2kΩ resistance which is connected in the collector is 2V. Find the base current.

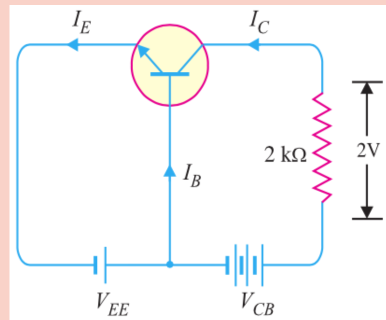
Solution

$$I_C = 2\text{ V}/2\text{ k}\Omega = 1\text{ mA}$$

$$\alpha = \frac{I_C}{I_E}$$

$$I_E = \frac{I_C}{\alpha} = \frac{1}{0.95} = 1.05\text{ mA}$$

$$I_B = I_E - I_C = 1.05 - 1 = \mathbf{0.05\text{ mA}}$$



Transistor currents and voltages.

I_B: dc base current
I_E: dc emitter current
I_C: dc collector current

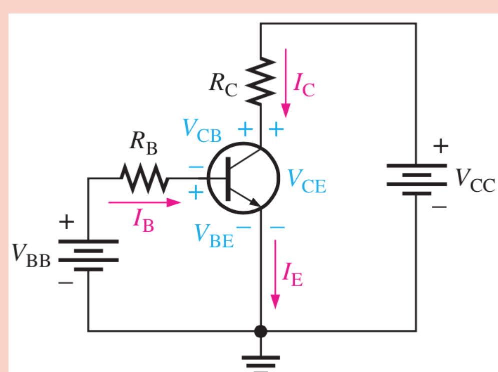
V_{BE}: dc voltage at base with respect to emitter (=0.7 V)

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter

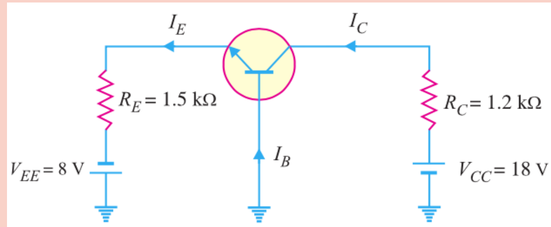
V_{BB} forward-biases the base-emitter junction

V_{EE} reverse-biases the base-collector junction



Example 4

For the common base circuit shown, determine I_C and V_{CB}. Assume the transistor to be of silicon.



Solution

Since the transistor is of silicon, V_{BE} = 0.7V. Applying Kirchhoff's law to the emitter-side loop, we get,

$$V_{EE} = I_E R_E + V_{BE}$$

$$I_E = \frac{V_{EE} - V_{BE}}{R_E}$$

$$\therefore \quad I_C \simeq I_E = \frac{8V - 0.7V}{1.5\ \text{k}\Omega} = 4.87\ \text{mA}$$

Applying Kirchhoff's voltage law to the collector-side loop, we have,

$$V_{CC} = I_C R_C + V_{CB}$$

$$\therefore \quad V_{CB} = V_{CC} - I_C R_C$$

$$= 18\ \text{V} - 4.87\ \text{mA} \times 1.2\ \text{k}\Omega = \mathbf{12.16\ V}$$

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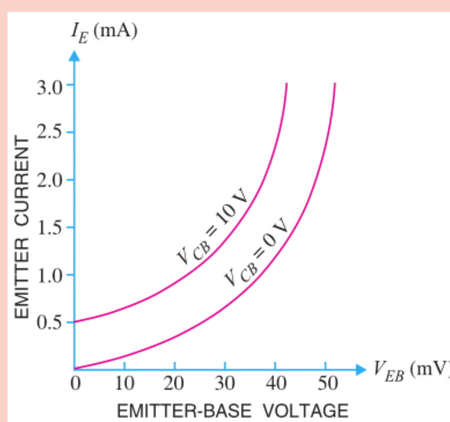
Characteristics of Common Base Connection

The most important characteristics of common base connection are *input characteristics* and *output characteristics*.

Input characteristic: It is the curve between emitter current I_E and emitter-base voltage V_{EB} at constant collector-base voltage V_{CB}.

(*i*) The emitter current I_E increases rapidly with small increase in emitter-base voltage V_{EB}. It means that input resistance is very small.

(*ii*) The emitter current is almost independent of collector-base voltage V_{CB}. This leads to the conclusion that emitter current (and hence collector current) is almost independent of collector voltage.



$$r_i = \frac{\Delta V_{BE}}{\Delta I_E}$$

Input resistance at constant V_{CB}

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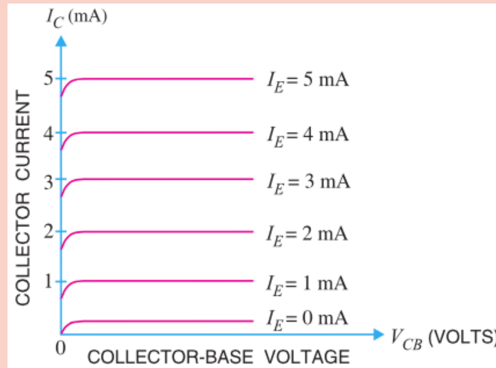
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Output characteristic: It is the curve between collector current I_C and collector-base voltage V_{CB} at constant emitter current I_E.

(i) The collector current I_C varies with V_{CB} only at very low voltages (<1V). The transistor is *never* operated in this region.

(ii) When the value of V_{CB} is raised above 1−2V, the collector current becomes constant. It means that now I_C is independent of V_{CB} and depends upon I_E only. This is consistent with the theory that the emitter current flows *almost* entirely to the collector terminal. The transistor is *always* operated in this region.

(iii) A very large change in collector-base voltage produces only a tiny change in collector current. This means that output resistance is very high.

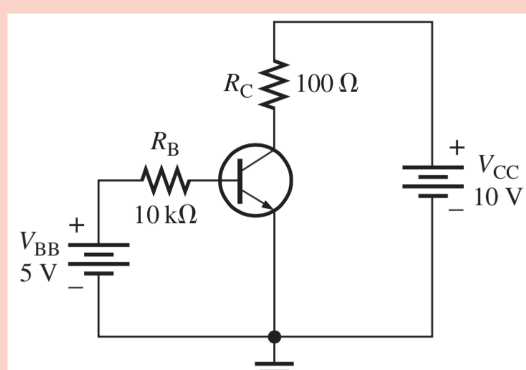


$$r_o = \frac{\Delta V_{CB}}{\Delta I_C}$$

Output resistance at constant I_E

Problem

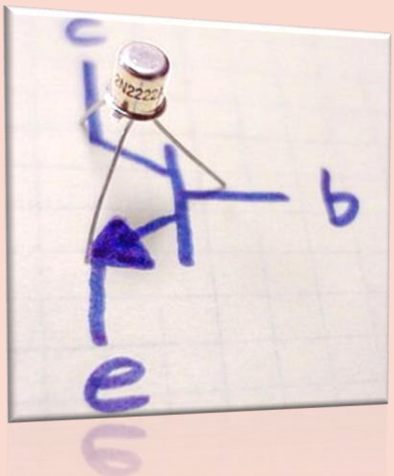
Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit. The transistor has a β_{DC} = 150.



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Electronic Fundamentals

Circuits, Devices, and Applications

Unit 4: Bipolar Junction Transistors (BJT)

Lecture 15: Transistor Connections

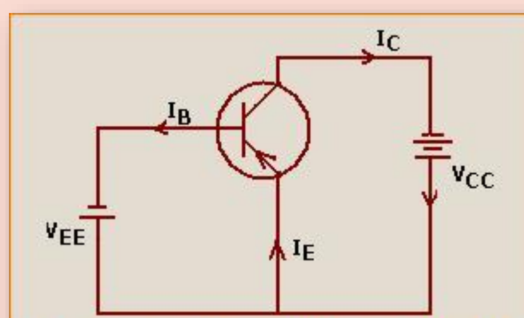
Common Emitter Connection

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Unit 4: Bipolar Junction Transistors (BJT)

- Transistor construction
- Transistor operation
- Transistor amplifying action
- BJT Characteristics and Parameters
- Transistor connections and characteristics
  - Common Base Connection
  - Common Emitter configuration
  - common collector connection



Common emitter configuration (P-N-P)

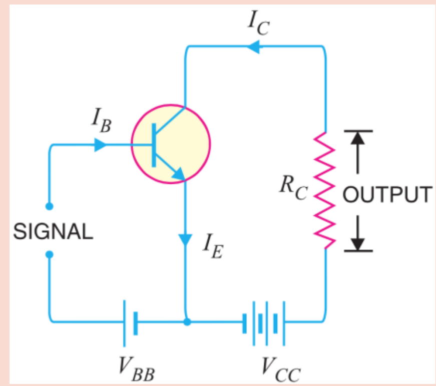
Common Emitter Connection

In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter.

(1) Base current amplification factor (β).

In common emitter connection, input current is I_B and output current is I_C.

The ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) is known as **base current amplification factor** *i.e.*



$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

In almost any transistor, less than 5% of emitter current flows as the base current. Usually, β in the ranges from 20 to 500. This type of connection is frequently used as it gives appreciable current gain as well as voltage gain.

(1) Relation between β and α. A simple relation between β and α can be derived as follows:

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

$$\beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha}{1-\alpha}$$

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\alpha = \frac{\beta}{1+\beta}$$

As α approaches unity, β approaches infinity. i.e., the current gain in common emitter connection is very high. It is due to this reason that this circuit arrangement is used in about 90 to 95 percent of all transistor applications.

Example 1

Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99.

Solution:

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9}{1-0.9} = 9$$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$$

Note: As α approaches unity, β approaches infinity.

Example 2

Calculate I_E in a transistor for which β = 50 and I_B = 20 μA.

Solution:

$$\beta = 50, \quad I_B = 20\mu A = 0.02 \text{ mA}$$

$$\beta = \frac{I_C}{I_B}$$

$$I_C = \beta I_B = 50 \times 0.02 = 1 \text{ mA}$$

$$I_E = I_B + I_C = 0.02 + 1 = \mathbf{1.02 \text{ mA}}$$

(2) Expression for collector current. In common emitter circuit, I_B is the input current and I_C is the output current.

$$I_E = I_B + I_C \quad \& \quad I_C = \alpha I_E + I_{CBO}$$

$$I_C = \alpha I_E + I_{CBO} = \alpha (I_B + I_C) + I_{CBO}$$

$$I_C (1-\alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$$

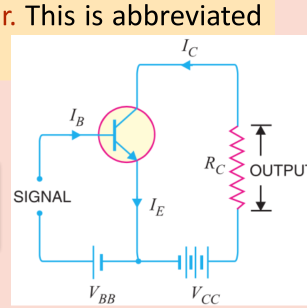
If I_B = 0, the collector current will be the current to the emitter. This is abbreviated as I_{CEO}, meaning collector-emitter current with base open.

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$$

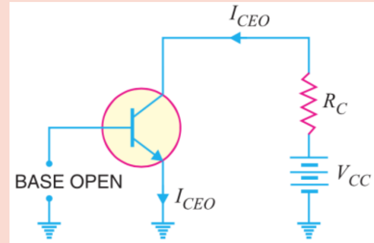
$$I_C = \frac{\alpha}{1-\alpha} I_B + I_{CEO}$$

$$\beta = \frac{\alpha}{1-\alpha}$$

$$I_C = \beta I_B + I_{CEO}$$



Concept of I_{CEO}. In *CE* configuration, a small collector current flows even when the base current is zero. This is the collector cut off current (*i.e.* the collector current that flows when base is open) and is denoted by I_{CEO}. The value of I_{CEO} is much larger than I_{CBO}.



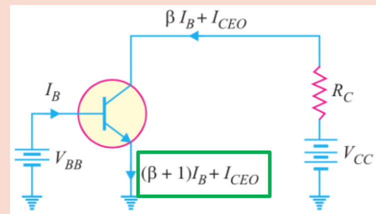
When the base voltage is applied as shown, then the various currents are :

$$\text{Base current} = I_B$$

$$\text{Collector current} = \beta I_B + I_{CEO}$$

$$\text{Emitter current} = \text{Collector current} + \text{Base current}$$

$$= (\beta I_B + I_{CEO}) + I_B = (\beta + 1) I_B + I_{CEO}$$



It may be noted here that from previous slide:

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = (\beta + 1) I_{CBO}$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \alpha = \frac{\beta}{1+\beta}$$

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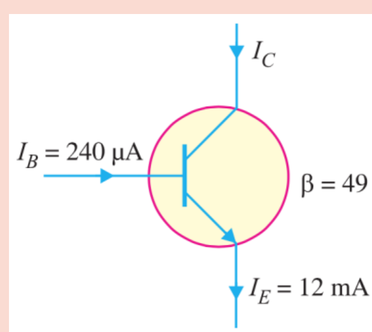
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Example 3

Find the α rating of the transistor shown. Determine the value of I_C using both α and β rating of the transistor.

Solution:

$$\alpha = \frac{\beta}{1+\beta} = \frac{49}{1+49} = \mathbf{0.98}$$



The value of I_C can be found by using either α or β rating

$$I_C = \alpha I_E = 0.98\ (12\ mA) = \mathbf{11.76\ mA}$$

$$I_C = \beta I_B = 49\ (240\ \mu A) = \mathbf{11.76\ mA}$$

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Example 4

For a transistor, β = 45 and voltage drop across 1kΩ which is connected in the collector circuit is 1 volt. Find the base current for common emitter connection.

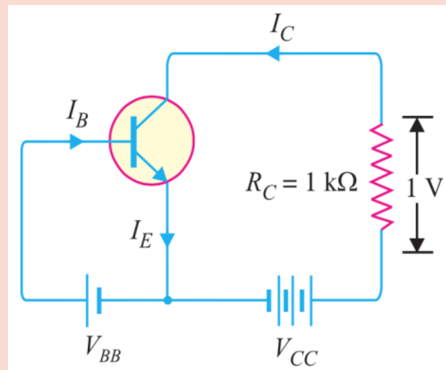
Solution:

The voltage drop across R_C (= 1 kΩ) is 1volt.

$$I_C = \frac{1\,V}{1\,k\Omega} = 1\text{ mA}$$

$$\beta = \frac{I_C}{I_B}$$

$$I_B = \frac{I_C}{\beta} = \frac{1}{45} = \mathbf{0.022\text{ mA}}$$



Example 5

A transistor is connected in common emitter (CE) configuration in which collector supply is 8V and the voltage drop across resistance R_C connected in the collector circuit is 0.5V. The value of R_C = 800 Ω. If α = 0.96, determine: (i) collector-emitter voltage (ii) base current I_B.

Solution:

(i) Collector-emitter voltage,

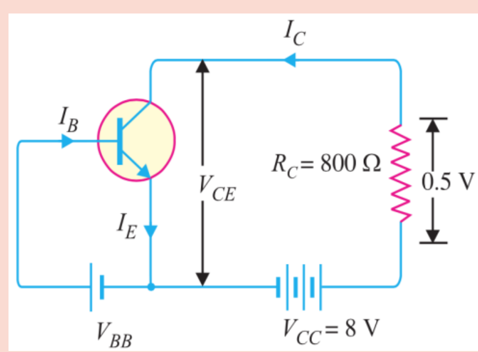
$$V_{CE} = V_{CC} - 0.5 = 8 - 0.5 = \mathbf{7.5\text{ V}}$$

(ii) The voltage drop across R_C(=800Ω) is 0.5V.

$$I_C = \frac{0.5\text{ V}}{800\,\Omega} = \frac{5}{8}\text{ mA} = 0.625\text{ mA}$$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

$$I_B = \frac{I_C}{\beta} = \frac{0.625}{24} = \mathbf{0.026\text{ mA}}$$



Example 6

Determine V_{CB} in the transistor circuit shown. The transistor is of silicon and has β = 150.

Solution:

Applying Kirchhoff's voltage law to base-emitter loop, we have, $V_{BB} - I_B R_B - V_{BE} = 0$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5V - 0.7V}{10\,k\Omega} = 430\ \mu A$$

$$I_C = \beta I_B = (150)(430\ \mu A) = 64.5\ mA$$

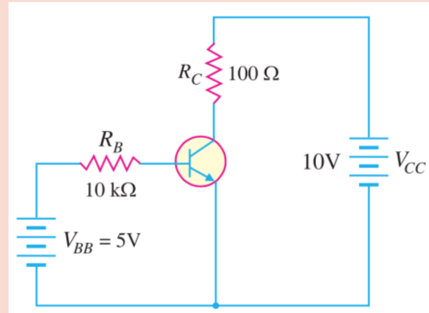
From the the collector-emitter loop, we have

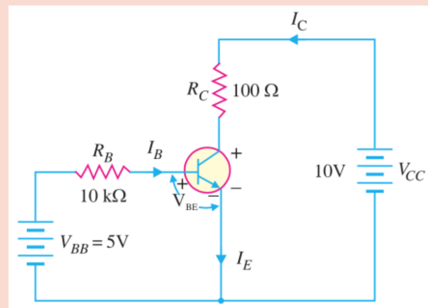
$$V_{CE} = V_{CC} - I_C R_C$$

$$= 10V - (64.5\ mA)\ (100\Omega) = 10V - 6.45V = 3.55V$$

$$V_{CE} = V_{CB} + V_{BE}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55 - 0.7 = \mathbf{2.85V}$$



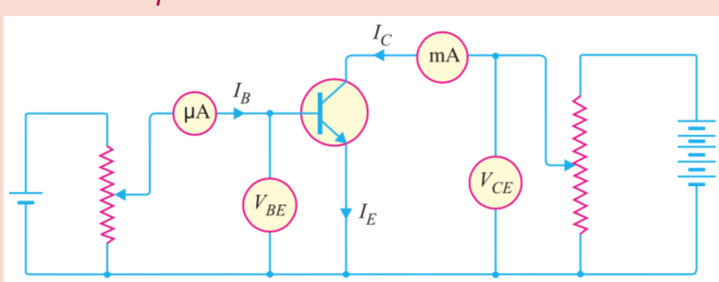


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Characteristics of Common Emitter Connection

The important characteristics of this circuit arrangement are the *input characteristics* and *output characteristics*.



The input characteristics of a *CE* connection can be determined by the circuit shown. Keeping V_{CE} constant (say at 10 V), note the base current I_B for various values of V_{BE}.

The output characteristics of a *CE* circuit can be drawn with the help of the circuit shown. Keeping the base current I_B fixed at some value say, 5 μA, note the collector current I_C for various values of V_{CE}.

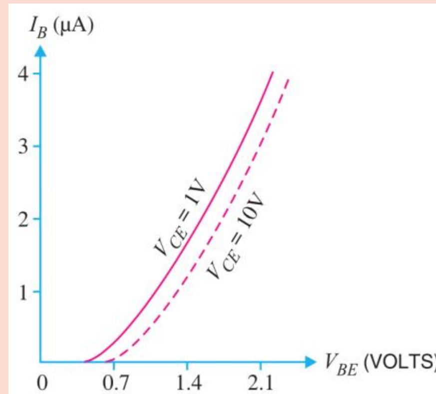
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Input characteristic. *It is the curve between base current I_B and base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE}.*

(*i*) The characteristic resembles that of a forward biased diode curve. This is expected since the base-emitter section of transistor is a diode and it is forward biased.

(*ii*) As compared to *CB* arrangement, I_B increases less rapidly with V_{BE}. Therefore, input resistance of a *CE* circuit is higher than that of *CB* circuit.



Input resistance $$r_i = \frac{\Delta V_{BE}}{\Delta I_B}$$ at constant V_{CE}

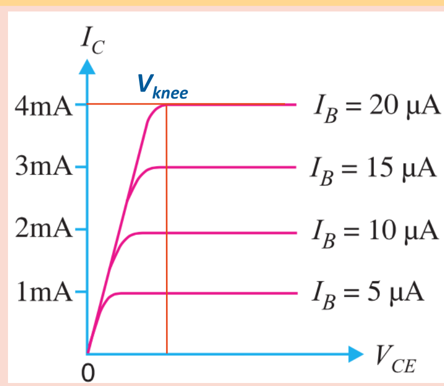
The value of input resistance for a *CE* circuit is of the order of a few hundred ohms.

Output characteristic. *It is the curve between collector current I_C and collector-emitter voltage V_{CE} at constant base current I_B.*

(*i*) The collector current I_C varies with V_{CE} for V_{CE} between 0 and 1V only. After this, collector current becomes *almost* constant and independent of V_{CE}. This value of V_{CE} upto which collector current I_C changes with V_{CE} is called the *knee voltage* (V_{knee}). *The transistors are always operated in the region above knee voltage.*

(*ii*) Above knee voltage, I_C is almost constant. However, a small increase in I_C with increasing V_{CE} is caused by the collector depletion layer getting wider and capturing a few more majority carriers before electron-hole combinations occur in the base area.

(*iii*) For any value of V_{CE} above knee voltage, the collector current I_C is approximately equal to β I_B.



Output resistance

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C}$$ at constant I_B

Its value is of the order of 50 kΛ.

Problem to Solve by Yourself

(1) The collector leakage current in a transistor is 300 μA in CE arrangement. If now the transistor is connected in CB arrangement, what will be the leakage current? Assume β = 120.

(2) For a certain transistor, I_B = 20 μA; I_C = 2 mA and β = 80. Calculate I_{CBO}.

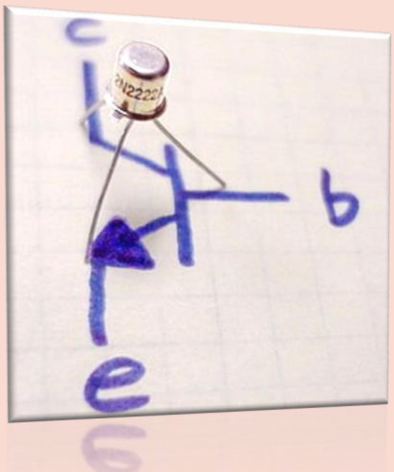
(3) In a transistor, I_B = 68 μA, I_E = 30 mA and β = 440. Determine α rating of the transistor. Then determine the value of I_C using both the α rating and β rating of the transistor.

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Circuits, Devices, and Applications



Unit 4: Bipolar Junction Transistors (BJT)

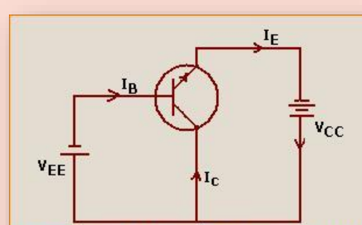
Lecture 16: Transistor Connections

Common Collector Connection

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Unit 4: Bipolar Junction Transistors (BJT)

- Transistor construction
- Transistor operation
- Transistor amplifying action
- BJT Characteristics and Parameters
- Transistor connections and characteristics
  - Common Base Connection
  - Common Emitter configuration
  - common collector connection



Common collector configuration (N-P-N)

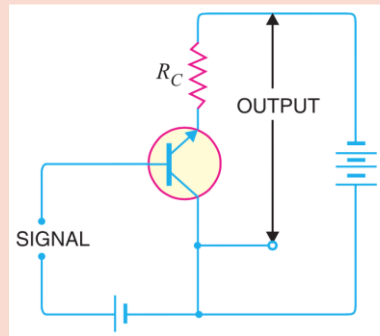
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Common Collector Connection

In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector.

(*i*) Current amplification factor γ. In common collector circuit, input current is the base current I_B and output current is the emitter current I_E.

The ratio of change in emitter current (ΔI_E) to the change in base current (ΔI_B) is known as **current amplification factor** *in common collector arrangement*



$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

This circuit provides about the same current gain as the common emitter circuit as $\Delta I_E \approx \Delta I_C$. However, its voltage gain is always less than 1.

Relation between γ and α

We have → $\alpha = \frac{\Delta I_C}{\Delta I_E}$ $\gamma = \frac{\Delta I_E}{\Delta I_B}$ $I_E = I_B + I_C$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

Substituting the value of ⊗I_B in

$$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$$

$$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{1}{1-\alpha}$$

$$\gamma = \frac{1}{1-\alpha}$$

Expression for collector current

We know $$I_C = \alpha I_E + I_{CBO}$$

Also $$I_E = I_B + I_C = I_B + (\alpha I_E + I_{CBO})$$

$$I_E (1 - \alpha) = I_B + I_{CBO}$$

$$I_E = \frac{I_B}{1 - \alpha} + \frac{I_{CBO}}{1 - \alpha}$$

$$I_C \; ; \; I_E = (\beta + 1)\, I_B + (\beta + 1)\, I_{CBO}$$

Applications of the CC circuit

The common collector circuit has very high input resistance (about 750kΩ) and very low output resistance (about 25 Ω).

Due to this reason, the voltage gain provided by this circuit is always less than 1.

Therefore, this circuit arrangement is seldom used for amplification.

However, due to relatively high input resistance and low output resistance, this circuit is primarily used for impedance matching *i.e.* for driving a low impedance load from a high impedance source.

Comparison of Transistor Connections

Characteristic	Common base	Common emitter	Common collector
Input resistance	Low (about 100 Ω)	Low (about 750 Ω)	Very high (about 750 kΩ)
Output resistance	Very high (about 450 kΩ)	High (about 45 kΩ)	Low (about 50 Ω)
Voltage gain	about 150	about 500	less than 1
Applications	For high frequency Applications	For audio frequency Applications	For impedance matching
Current	No (less than 1)	High (β)	Appreciable

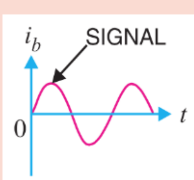
Out of the three transistor connections, the common emitter circuit is the most efficient

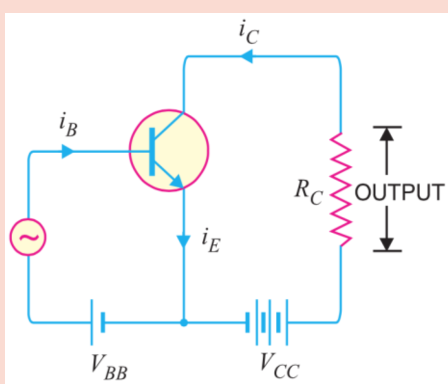
(i) High current gain
(ii) High voltage and power gain
(iii) Moderate output to input impedance ratio

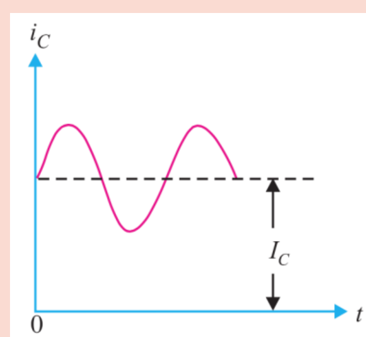
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Transistor as an Amplifier in *CE* Arrangement







Note that a battery V_{BB} is connected in the input circuit in addition to the signal voltage. This dc voltage is known as *bias voltage* and its magnitude is such that it always keeps the emitter-base junction forward biased regardless of the polarity of the signal source.

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Operation

During the positive half-cycle of the signal, the forward bias across the emitter-base junction is increased.

Therefore, more electrons flow from the emitter to the collector *via* the base. This causes an increase in collector current.

The increased collector current produces a greater voltage drop across the collector load resistance R_C.

During the negative half-cycle of the signal, the forward bias across emitter-base junction is decreased.

Therefore, collector current decreases. This results in the decreased output voltage (in the opposite direction). Hence, an amplified output is obtained across the load.

Analysis of collector currents

When no signal is applied, the input circuit is forward biased by the battery V_{BB}. Therefore, a d.c. collector current I_C flows in the collector circuit. This is called *zero signal collector current*.

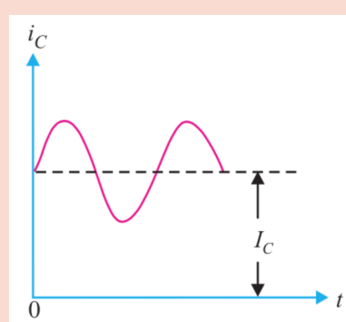
When the signal voltage is applied, the forward bias on the emitter- base junction increases or decreases depending upon whether the signal is positive or negative.

The total collector current consists of two components;

(i) The dc collector current I_C (zero signal collector current) due to bias battery V_{BB}. This is the current that flows in the collector in the absence of signal.

(ii) The ac collector current i_c due to signal.

∴ Total collector current, $i_C = i_c + I_C$



The table below gives the symbols usually employed for currents and voltages in transistor applications.

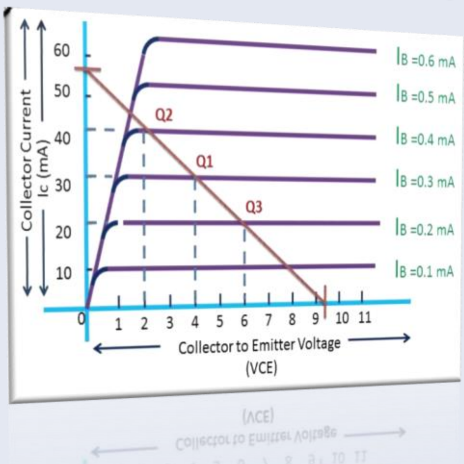
Particular	Instantaneous a.c.	d.c.	Total
Emitter current	i_e	I_E	i_E
Collector current	i_c	I_C	i_C
Base current	i_b	I_B	i_B
Collector-emitter voltage	v_{ce}	V_{CE}	v_{CE}
Emitter-base voltage	v_{eb}	V_{EB}	v_{EB}

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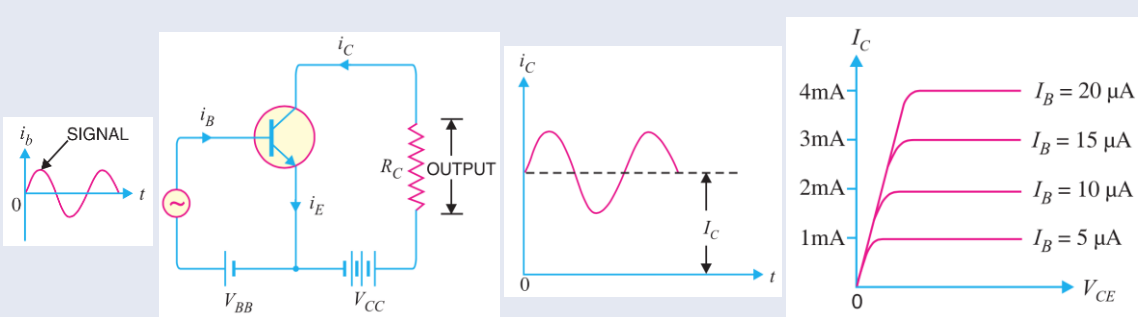
Unit 5: DC Biasing of BJTs
Lecture 17: Transistor Load Line
Analysis: *DC Load Line and Q-Point*

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1

Introduction

- A transistor must be properly biased with a dc voltage in order to operate as a linear amplifier.
- A dc operating point **Q-point (quiescent point)** must be set so that signal variations at the input terminal are amplified and accurately reproduced at the output terminal.

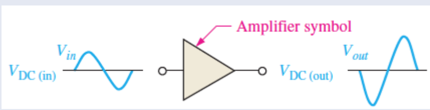


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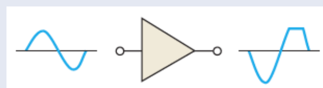
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Importance of Biasing

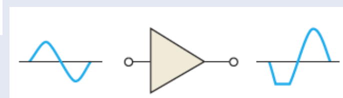
Bias establishes the dc operating point (**Q-point**) for proper linear operation of an amplifier. If an amplifier is not biased with correct dc voltages on the input and output, it can go into saturation or cutoff when an input signal is applied.



Linear operation: larger output has same shape as input except that it is inverted.



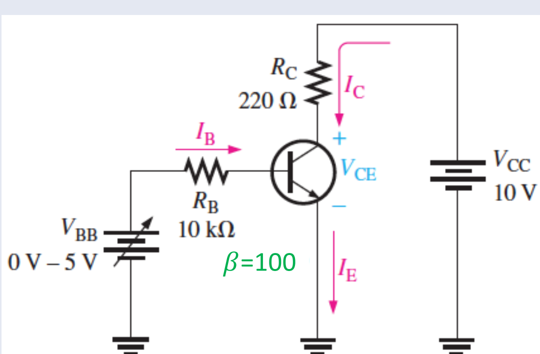
Nonlinear operation: output voltage limited (clipped) by cutoff

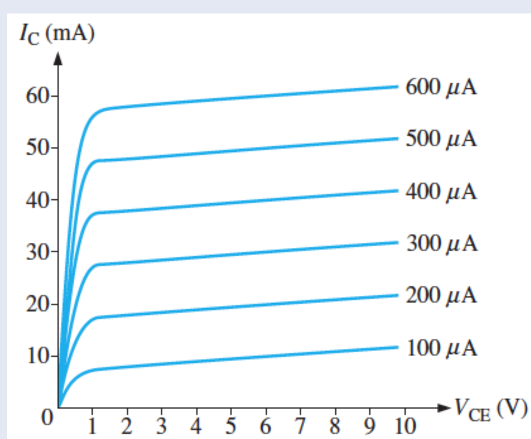


Nonlinear operation: output voltage limited (clipped) by saturation

Effect of dc Bias

The transistor shown is biased with V_{CC} and V_{BB} to obtain certain values of I_B, I_C, I_E, and V_{CE}.





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For I_B of 200 mA

Adjusting V_{BB} to produce an I_B of 200 mA.

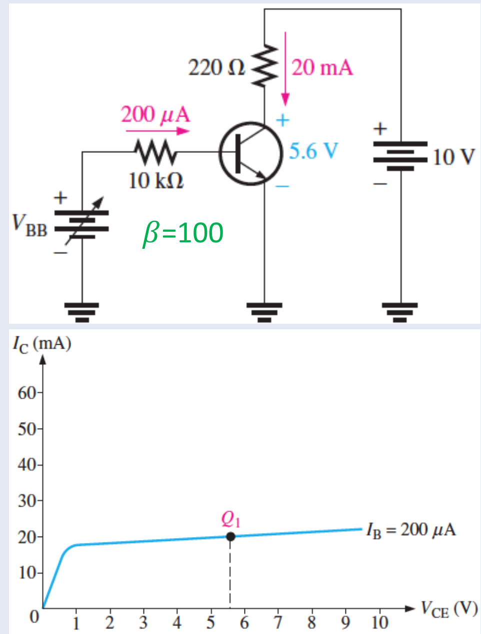
Since $I_C = \beta\ I_B$, the collector current is 20 mA, as indicated, and

$V_{CE} = V_{CC} - I_C R_C$

$= 10V - (20mA)(220\Omega) = 10V - 4.4V$

$= 5.6V$

This Q-point is shown as Q_1



For I_B of 300 mA

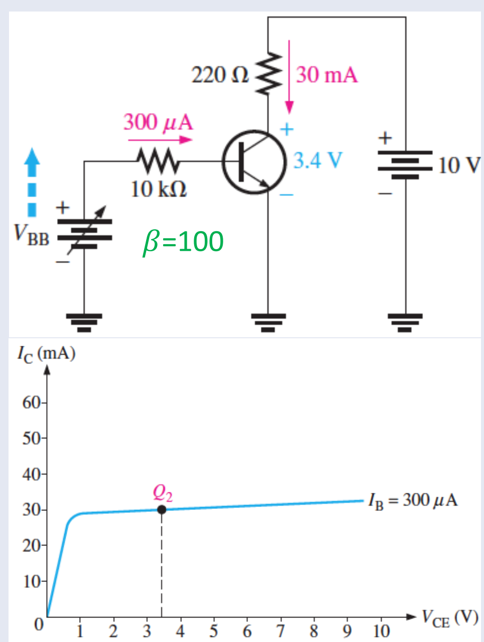
V_{BB} is increased to produce an I_B of 300 mA and an

I_C of 30 mA.

$V_{CE} = 10V - (30mA)(220\ \Omega)$

$= 10V - 6.6V = 3.4V$

This Q-point is shown as Q_2



For I_B of 400 mA

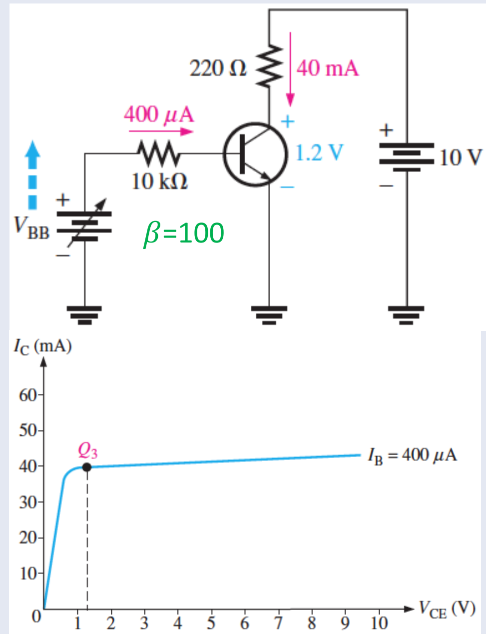
V_{BB} is increased to give an I_B of 400 mA and an

I_C of 40 mA.

V_{CE} = 10V - (40mA)(220 Ω)

= 10V - 8.8V = 1.2V

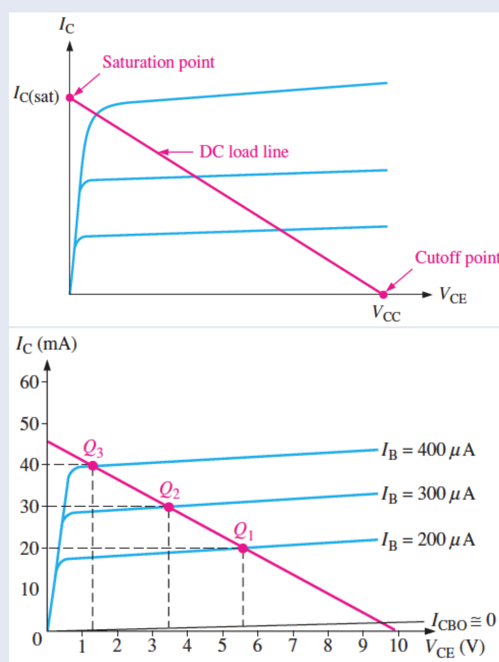
This Q-point is shown as Q_2



DC Load Line

This is a straight line drawn on the characteristic curves from the saturation value where $I_C = I_{C(sat)}$ on the *y*-axis to the cutoff value where $V_{CE} = V_{CC}$ on the *x*-axis.

The point at which the load line intersects a characteristic curve represents the Q-point for that particular value of I_B.



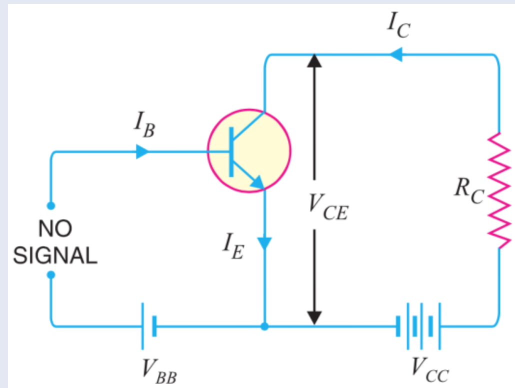
Consider a common emitter *npn* transistor circuit shown where no signal is applied.

The value of collector-emitter voltage V_{CE} at any time is given by;

$$V_{CE} = V_{CC} - I_C R_C$$

To add load line, we need two end points of the straight line. These two points can be located as under:

- When the collector current $I_C = 0$
- When collector-emitter voltage $V_{CE} = 0$



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(i) The first point:

When the collector current $I_C = 0$, then collector-emitter voltage is maximum and is equal to V_{CC} *i.e.*

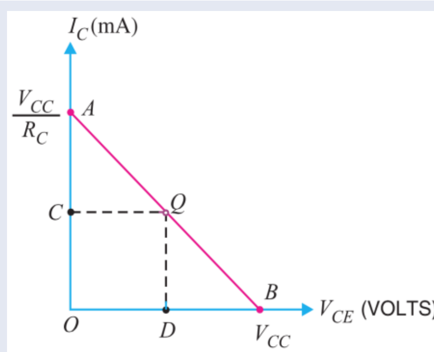
∴ Max. $V_{CE} = V_{CC} - I_C R_C = V_{CC}$

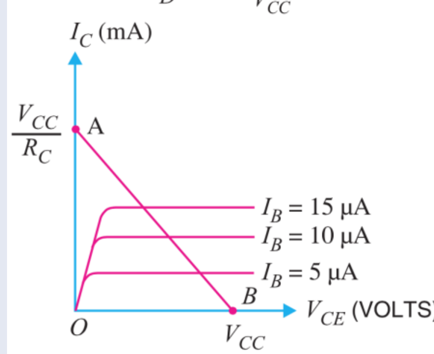
(ii) The second point

When collector-emitter voltage $V_{CE} = 0$, the collector current is maximum and is equal to V_{CC} / R_C *i.e.*

$V_{CE} = V_{CC} - I_C R_C$ or $0 = V_{CC} - I_C R_C$

∴ Max. $I_C = V_{CC} / R_C$



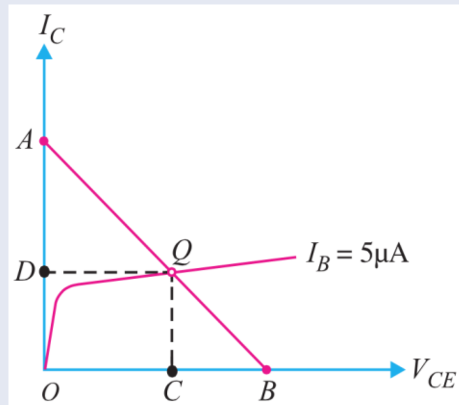


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Operating Point

The zero signal values of I_C and V_{CE} are known as the **operating point** "because the variations of I_C and V_{CE} take place about this point when signal is applied".

It is also called quiescent (silent) point or *Q-point* because it is the point on I_C – V_{CE} characteristic when the transistor is silent *i.e.* in the absence of the signal.



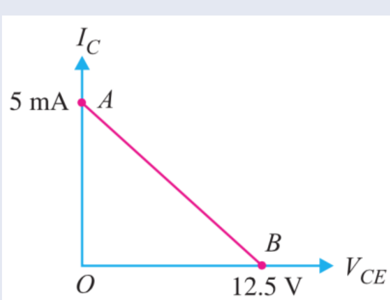
Example 1

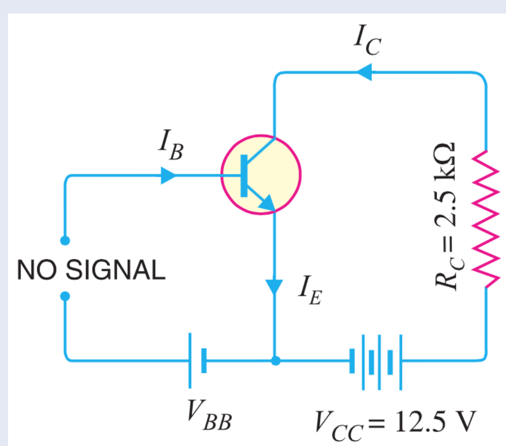
Draw the dc load line for the circuit shown.

Solution:

When $V_{CE} = 0$, then,

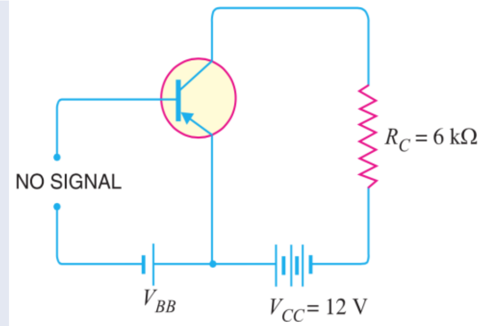
$I_C = V_{CC}/R_C = 12.5V/2.5k\Omega = 5mA$





Example 2

In the circuit diagram shown, if V_{CC} = 12V and R_C = 6 kΩ, draw the dc load line. What will be the Q point if zero signal base current is 20μA and β = 50?



Solution:

V_{CE} is given by $V_{CE} = V_{CC} - I_C R_C$ When I_C =0, $V_{CE} = V_{CC}$ =12V.

When V_{CE} =0, $I_C = V_{CC}/R_C$ = 12 V/6 kΩ = 2 mA.

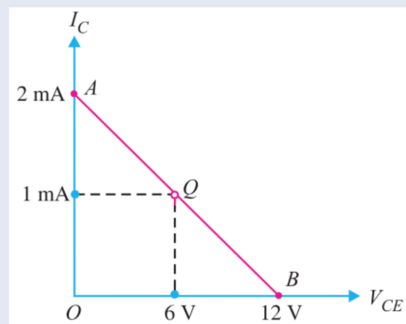
Zero signal base current, I_B = 20 μA, β = 50

Zero signal collector current, $I_C = \beta\, I_B$ = 50×0.02 = **1 mA**

Zero signal collector-emitter voltage is

$V_{CE} = V_{CC} - I_C R_C$ = 12 – 1mA × 6kΩ = **6V**

∴ Operating point is **6 V, 1 mA**.



Example 3

In a transistor circuit, collector load is 4 kΩ whereas quiescent current (zero signal collector current) is 1mA.

(i) What is the operating point if V_{CC} = 10V?

(ii) What will be the operating point if R_C = 5kΩ?

Solution:

(i) When collector load R_C = 4 kΩ

$V_{CE} = V_{CC} - I_C R_C$

= 10 – (1mA × 4kΩ) = 6V

Operating point is **6 V, 1 mA.**

(ii) When collector load R_C = 5kΩ

$V_{CE} = V_{CC} - I_C R_C$

= 10 – (1mA × 5kΩ)

V_{CE} = 10 – 5 = 5V

Operating point is **5 V, 1 mA**.

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Example 4

Determine the Q point of the transistor circuit shown. Also draw the dc load line. Given β = 200 and V_{BE} = 0.7V.

Solution:

$$V_{BB} - I_B R_B - V_{BE} = 0$$

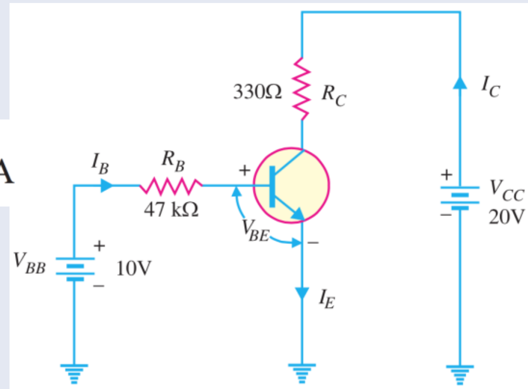
$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10V - 0.7V}{47\ k\Omega} = 198\ \mu A$$

$$I_C = \beta I_B = (200)(198\ \mu A) = 39.6\ mA$$

$$V_{CE} = V_{CC} - I_C R_C$$

$$= 20V - (39.6mA)(330\ \Omega)$$

$$= 20V - 13.07V = 6.93V$$



Therefore, the Q-point is
I_C = **39.6 mA** and V_{CE} = **6.93V**.

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D.C. load line

In order to draw the dc load line, we need two end points.

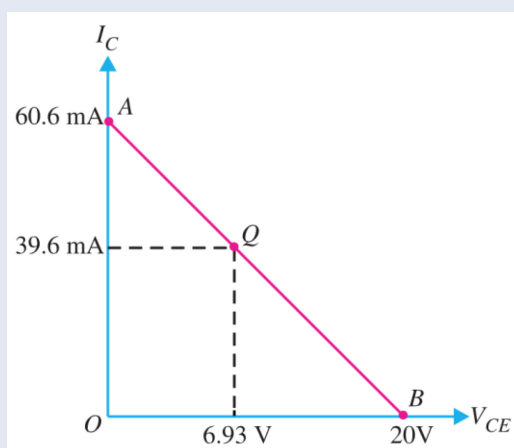
$$V_{CE} = V_{CC} - I_C R_C$$

When I_C = 0, V_{CE} = V_{CC} = 20V.

When V_{CE} = 0,

I_C = V_{CC}/R_C

= 20V/330Ω = 60.6 mA.

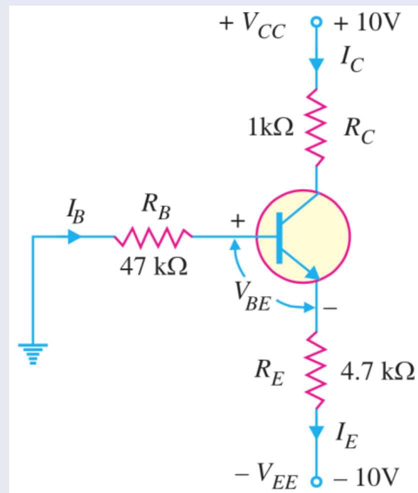


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Problem to solve by yourself

Determine the Q point of the transistor circuit shown. Also draw the dc load line. Given β = 100 and V_{BE} = 0.7V.



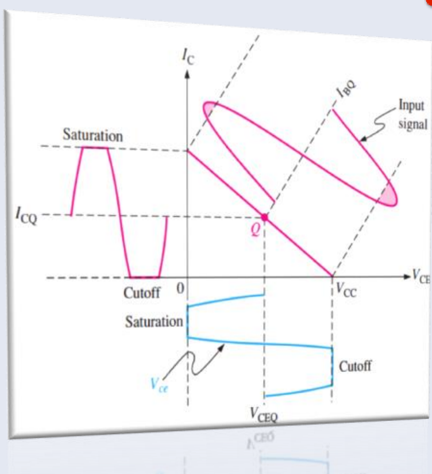
Hint: Apply Kirchhoff's voltage law to find the various voltages and currents in the circuit.

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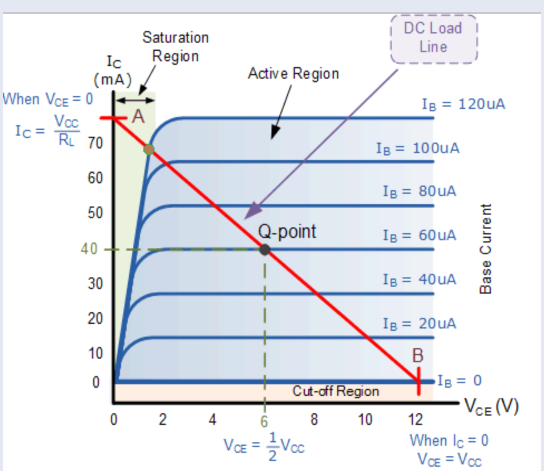
Unit 5: DC Biasing of BJTs

Lecture 18: Transistor Load Line Analysis: *Linear Operation*

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Al-Azhar University of Gaza

Linear Operation



The region along the load line including all points between saturation and cutoff is generally known as the **linear region** of the transistor's operation.

As long as the transistor is operated in this region, the output voltage is ideally a linear reproduction of the input.

Operation with ac signal

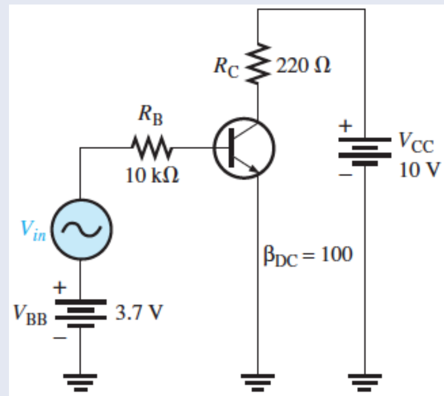
Assume a sinusoidal voltage, V_{in}, is superimposed on V_{BB} as shown.

The value of V_{CE}, I_C, and I_B at dc Q-point values with no input sinusoidal voltage applied are as follow:

$$I_{BQ} = \frac{V_{BB} - 0.7\ \text{V}}{R_B} = \frac{3.7\ \text{V} - 0.7\ \text{V}}{10\ \text{k}\Omega} = 300\ \mu\text{A}$$

$$I_{CQ} = \beta_{DC} I_{BQ} = (100)(300\ \mu\text{A}) = 30\ \text{mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C = 10\ \text{V} - (30\ \text{mA})(220\ \Omega) = 3.4\ \text{V}$$

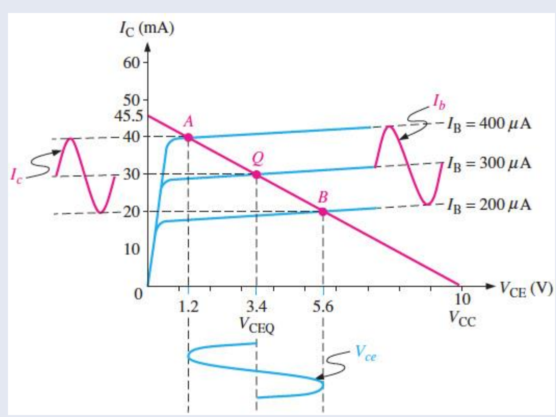


Operation with ac signal, continue

Applying a sinusoidal voltage, V_{in}, causing the base current to vary sinusoidally 100 μA above and below its Q-point value of 300 μA.

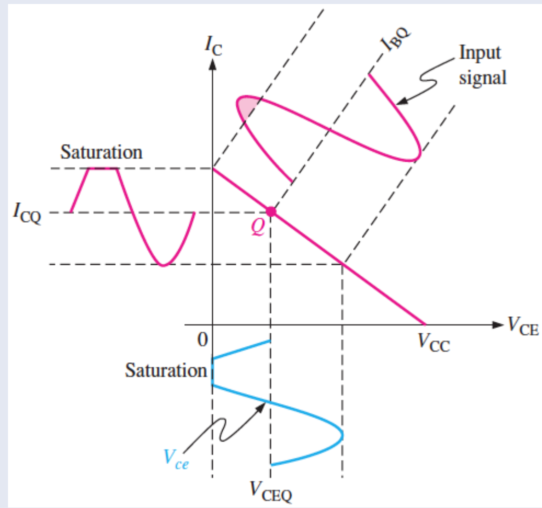
This, causes the collector current to vary 10 mA above and below its Q-point value of 30 mA.

As a result, the collector- to-emitter voltage varies 2.2 V above and below its Q-point value of 3.4 V.



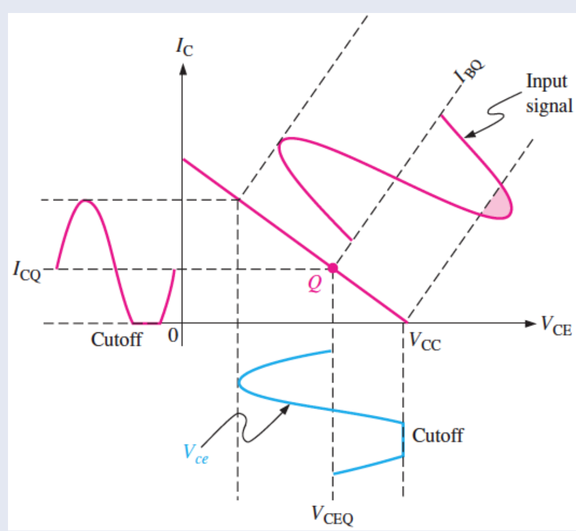
Waveform Distortion

Transistor is driven into saturation because the Q-point is too close to saturation for the given input signal.



Waveform Distortion, continue

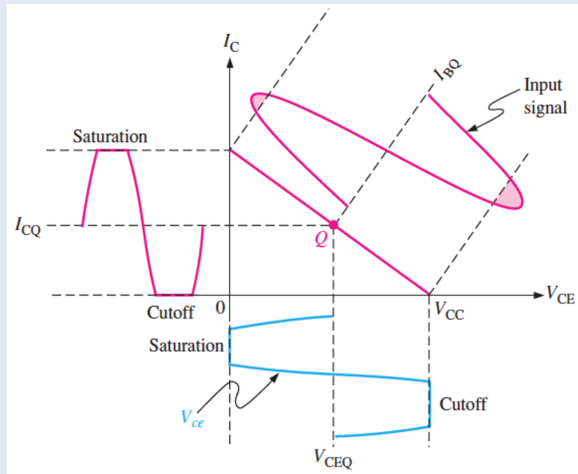
Transistor is driven into cutoff because the Q-point is V_{ce} too close to cutoff for the given input signal.



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Waveform Distortion, continue

Transistor is driven into both saturation and cutoff because the input signal is too large.



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Output from Transistor Amplifier

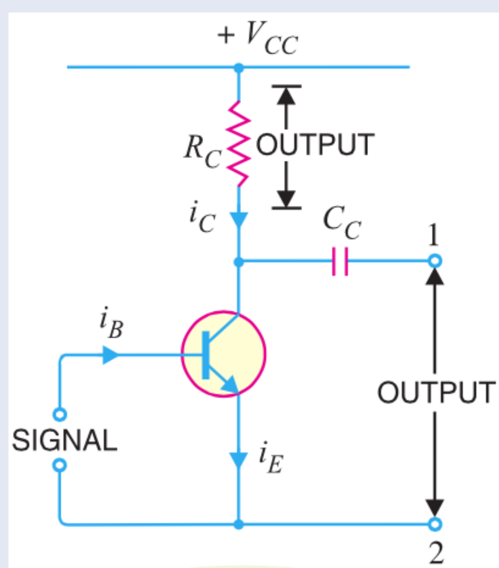
The output can be taken either across R_C or across terminals 1 and 2.

(i) First method.

We can take the output directly by putting a load resistance R_C in the collector circuit *i.e.*

Output = voltage across $R_C = i_c R_C$ (*i*)

This method of taking output from collector load is used only in single stage of amplification.



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(ii) Second method.

The output can also be taken across terminals 1 and 2 *i.e*. from collector and emitter end of supply.

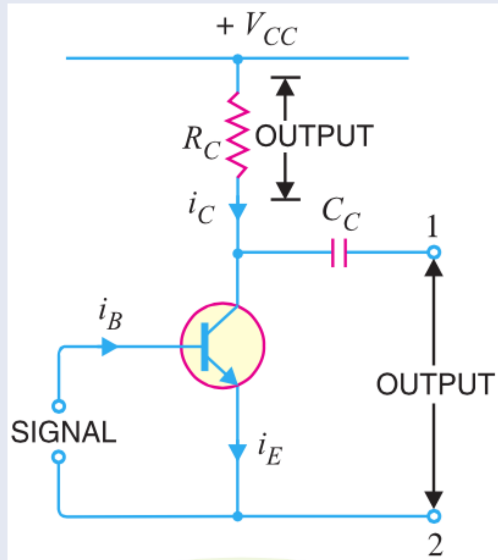
Output = Voltage across terminals 1 and 2

$$= V_{CC} - i_c R_C$$

As V_{CC} is a direct voltage and cannot pass through capacitor C_C, therefore, only varying voltage $i_c R_C$ will appear across terminals 1 and 2.

$$\therefore \text{Output} = -\, i_c R_C \qquad (ii)$$

The minus sign in simply indicates the phase reversal. The second method of taking output is used in multistages of amplification.



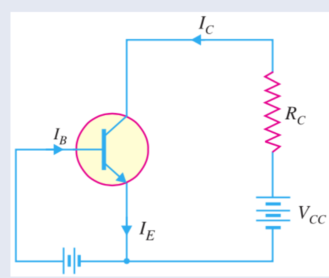
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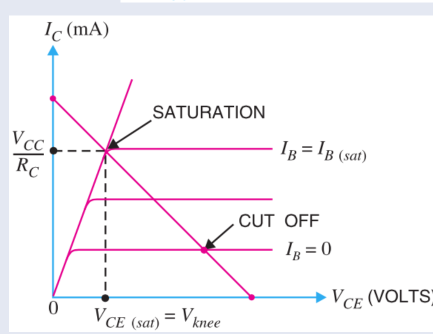
Cut off and Saturation Points

Cutoff: The point where the load line intersects the I_B = **0** curve is known as *cutoff*.

- At this point, I_B = 0 and only small collector current (*i.e*. collector leakage current I_{CEO}) exists.
- At cut off, \the base-emitter junction no longer remains forward biased and normal transistor action is lost.
- The collector-emitter voltage is nearly equal to V_{CC} *i.e.*

$$V_{CE\,(cut\,off)} = V_{CC}$$





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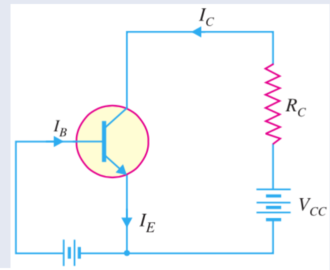
Cut off and Saturation Points

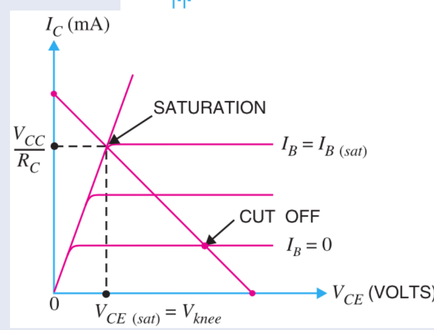
Saturation: The point where the load line intersects the $I_B = I_{B(sat)}$ curve is called *saturation*.

- At this point, the base current is maximum and so is the collector current.
- At saturation, collector- base junction no longer remains reverse biased and normal transistor action is lost.

$$I_{C\,(sat)} \simeq \frac{V_{CC}}{R_C}\,; \quad V_{CE} = V_{CE(sat)} = V_{knee}$$

- If base current is greater than $I_{B(sat)}$, then collector current cannot increase because collector-base junction is no longer reverse-biased.

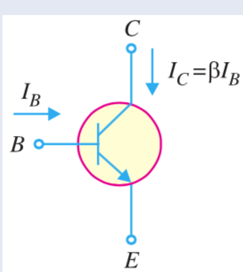




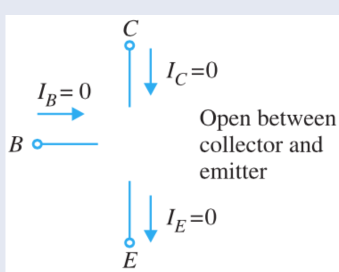
In the **active state**, collector current is β times the base current (*i.e.* $I_C = \beta I_B$).

If the transistor is **cut-off,** there is no base current, so there is no collector or emitter current. That is collector emitter pathway is open

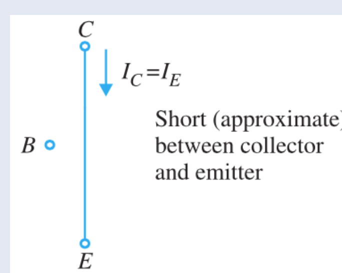
In **saturation**, the collector and emitter are, shorted together. That is the transistor behaves as though a switch has been closed between the collector and emitter.



Active state



Cut-off

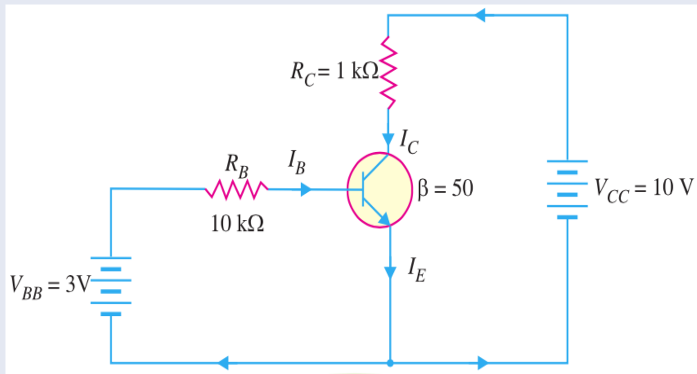


Saturation

Example 1

Determine whether or not the transistor is in saturation. Assume V_{knee}=0.2V.

Solution:



$$I_{C\,(sat)} = \frac{V_{CC} - V_{knee}}{R_C}$$

$$= \frac{10\,V - 0.2\,V}{1\,k\Omega}$$

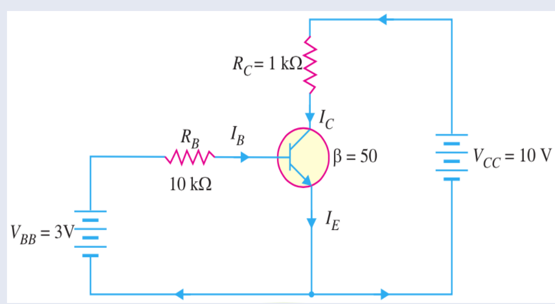
$$= \frac{9.8\,V}{1\,k\Omega} = 9.8\text{ mA}$$

Now we shall find out if I_B is large enough to produce $I_{C\,(sat)}$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

$$= \frac{3V - 0.7V}{10\,k\Omega} = \frac{2.3\,V}{10\,k\Omega} = 0.23\text{ mA}$$

$$I_C = \beta I_B = 50 \times 0.23 = 11.5\text{ mA}$$



This shows that with specified β, this base current (= 0.23 mA) is capable of producing I_C greater than $I_{C\,(sat)}$. Therefore, the transistor is **saturated.**

In fact, the collector current value of 11. 5 mA is never reached. If the base current value corresponding to $I_{C\ (sat)}$ is increased, the collector current remains at the saturated value (= 9.8 mA).

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Example 2

In the circuit shown, V_{BB} is set equal to the following values: (i) V_{BB} = 0.5V (ii) V_{BB} = 1.5V (iii) V_{BB} = 3V. Determine the state of the transistor for each value of the base supply voltage V_{BB}.

(i) For V_{BB} = 0.5V

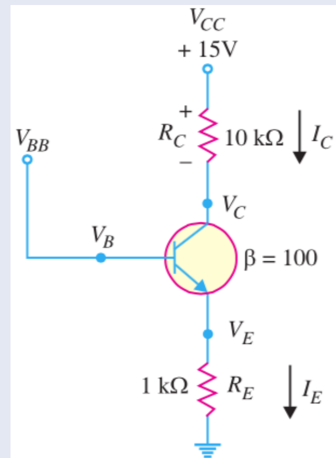
Because the base voltage V_B (= V_{BB} = 0.5V) is less than 0.7V, the transistor is **cut-off.**

(ii) For V_{BB} = 1.5V

The base voltage V_B controls the emitter voltage V_E which controls the emitter current I_E.

$$V_E = V_B - 0.7\text{V} = 1.5\text{V} - 0.7\text{V} = 0.8\text{V}$$

$$I_E = \frac{V_E}{R_E} = \frac{0.8\,V}{1\,k\Omega} = 0.8 \text{ mA}$$



If the transistor is active, we have,

$I_C = I_E$ = 0.8 mA and $I_B = I_C / \beta$ = 0.8/100 = 0.008mA

∴ Collector voltage, $V_C = V_{CC} - I_C R_C$

= 15V – 0.8 mA × 10 kΩ = 15V – 8V = 7V

Since $V_C > V_E$, the transistor is **active** and our assumption is correct.

(iii) For V_{BB} = 3V

$V_E = V_B - 0.7$ V = 3 V – 0.7 V = 2.3 V

$$I_E = \frac{V_E}{R_E} = \frac{2.3\,V}{1\,k\Omega} = 2.3 \text{ mA}$$

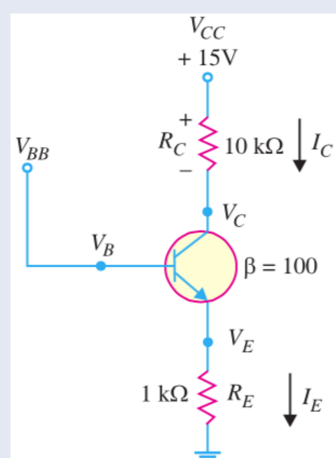
Assuming the transistor is active, we have,

$I_C = I_E$ = 2.3 mA; $I_B = I_C / \beta$ = 2.3 / 100 = 0.023mA

∴ Collector voltage, $V_C = V_{CC} - I_C R_C$

= 15 V – 2.3 mA × 10 kΩ = 15 V – 23 V = –8 V

Since $V_C < V_E$, the transistor is **saturated** and our assumption is not correct.



Power Rating of Transistor

The maximum power that a transistor can handle without destruction is known as **power rating** of the transistor.

When a transistor is in operation, almost all the power is dissipated at the reverse biased collector-base junction. The power rating (or maximum power dissipation) is given by:

$$P_{D\,(max)} = \text{Collector current} \cdot \text{Collector-base voltage}$$

$$P_{D\,(max)} = I_C \times V_{CB}$$

$$\therefore P_{D(max)} = I_C \times V_{CE}$$

[$V_{CE} = V_{CB} + V_{BE}$. Since V_{BE} is very small, $V_{CB} \cong V_{CE}$]

While connecting transistor in a circuit, it should be ensured that its power rating is not exceeded otherwise the transistor may be destroyed due to excessive heat.

Example 3

Suppose the power rating (or maximum power dissipation) of a transistor is 300 mW. If the collector current is 30 mA, what is the maximum allowed V_{CE}?

Solution:

$$P_{D\,(max)} = I_C \times V_{CE\,(max)}$$

$$300\text{ mW} = 30\text{ mA} \times V_{CE\,(max)}$$

$$V_{CE\,(max)} = \frac{300\text{ mW}}{30\text{ mA}} = 10\text{V}$$

This means that for I_C = 30 mA, the maximum V_{CE} allowed is 10V. If V_{CE} exceeds this value, the transistor will be destroyed due to excessive heat.

Maximum power dissipation curve

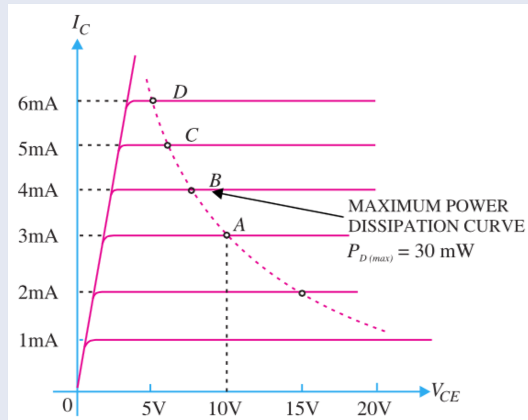
To draw this curve, we should know the power rating (*i.e.* maximum power dissipation) of the transistor. Suppose the power rating of a transistor is 30 mW.

$$P_{D\,(max)} = V_{CE} \times I_C$$

$$30\text{ mW} = V_{CE} \times I_C$$

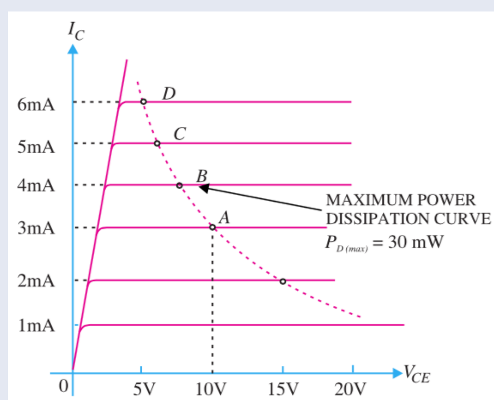
Using convenient V_{CE} values, for example V_{CE} = 10V

$$I_C\,(max) = \frac{P_{D\,(max)}}{V_{CE}} = \frac{30\text{ mW}}{10\text{ V}} = 3\text{mA}$$



This locates the point *A* (10V, 3 mA) on the output characteristics.

In order that transistor may not be destroyed, the transistor voltage and current (V_{CE} and I_C) conditions must at all times be maintained in the portion of the characteristics below the maximum power dissipation curve.



Example 4

The maximum power dissipation of a transistor is 100mW. If V_{CE} = 20V, what is the maximum collector current that can be allowed without destruction of the transistor?

Solution

$$P_{D\,(max)} = V_{CE} \times I_{C\,(max)}$$

$$100\text{ mW} = 20\text{ V} \times I_{C\,(max)}$$

$$I_{C\,(max)} = \frac{100\text{ mW}}{20\text{ V}} = 5\text{ mA}$$

Example 5

For the circuit shown, find the transistor power dissipation. Assume that β=200.

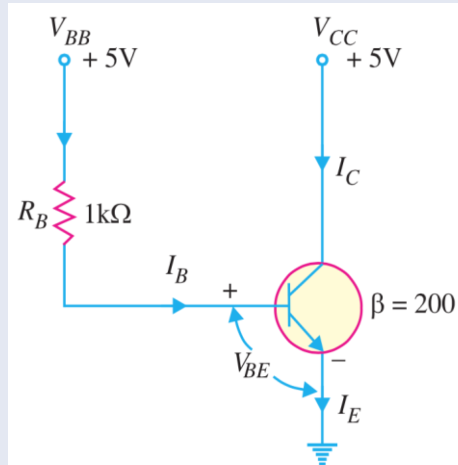
$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{(5-0.7)\,V}{1\,k\Omega} = 4.3\text{ mA}$$

$$I_C = \beta I_B = 200 \times 4.3 = 860\text{ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 5 - I_C \times 0 = 5\text{V}$$

$$\therefore \text{ Power dissipation, } P_D = V_{CE} \times I_C$$

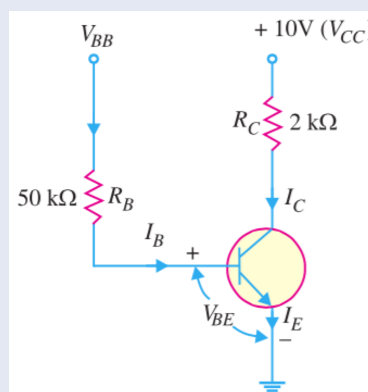
$$= 5\text{V} \times 860\text{ mA} = 4300\text{ mW} = \mathbf{4.3W}$$

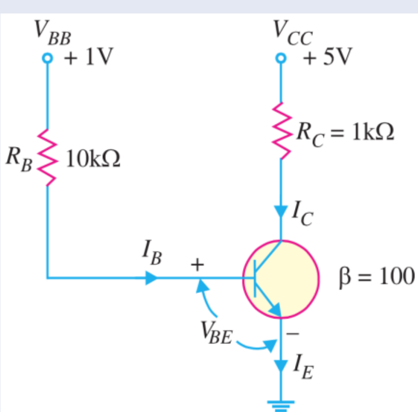


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Problem to solve by yourself

(1) *For the circuit in the figure, find the base supply voltage (V_{BB}) that just puts the transistor into saturation. Assume β = 200.*





(2) *For the circuit shown in, find the power dissipated in the transistor. Assume β = 100..*

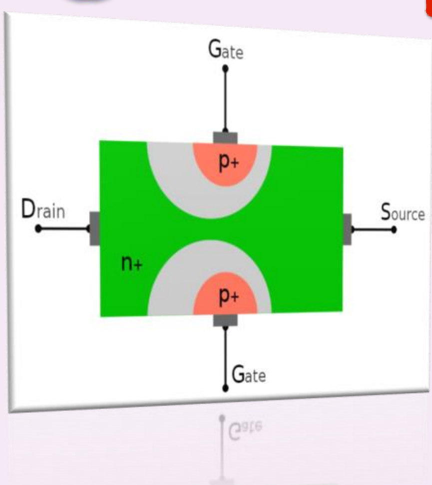
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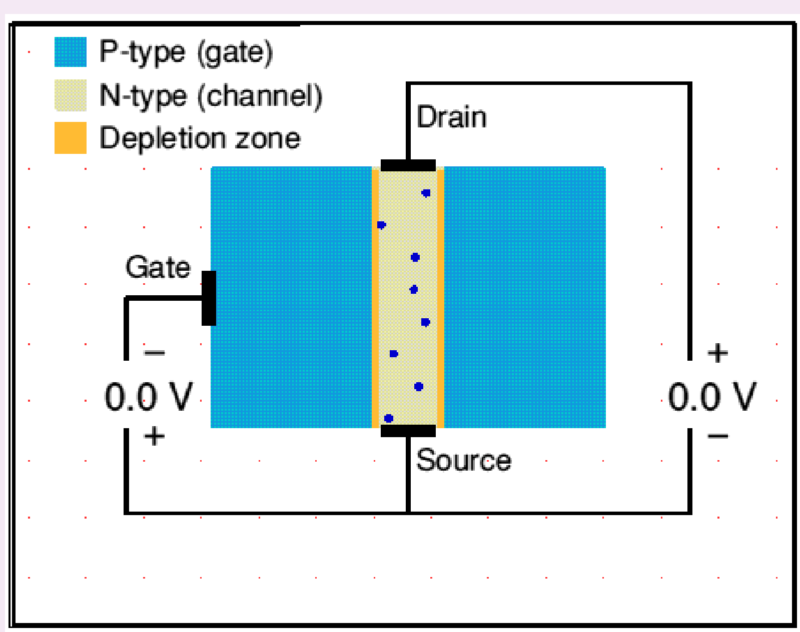


Unit 6: Field Effect Transistor (FET)

Lecture 19: Field Effect Transistor (FET)

Dr. Hazem Falah Sakeek

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Introduction

- In ordinary transistor, both holes and electrons play part in the conduction process. For this reason, it is called a bipolar transistor.
- The ordinary or bipolar transistor has two principal disadvantages.
  - **First,** it has a low input impedance because of forward biased emitter junction.
  - **Secondly,** it has considerable noise level, it is difficult to achieve input impedance more than a few megaohms.
- The **field effect transistor (*FET*)** has, by its construction and biasing, large input impedance which may be more than 100 megaohms.
- The *FET* is generally much less noisy than the ordinary or bipolar transistor.

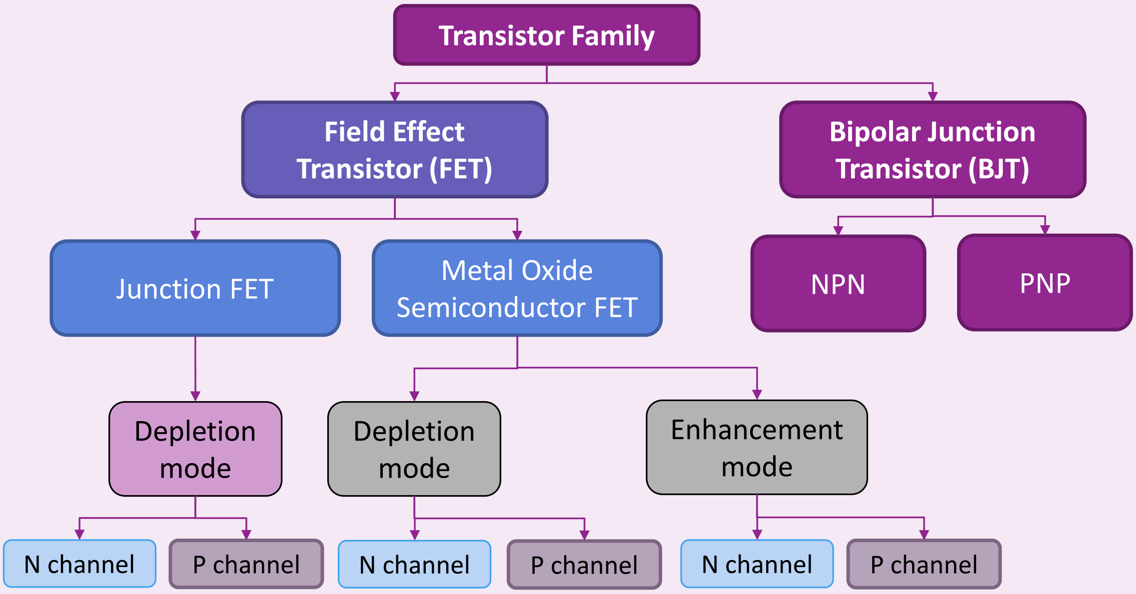
Types of Field Effect Transistors

A **bipolar junction transistor (*BJT*)** is a current controlled device *i.e.*, output characteristics of the device are controlled by base current and not by base voltage. However, in a **field effect transistor (*FET*)**, the output characteristics are controlled by input voltage (*i.e.*, electric field) and not by input current.

There are two basic types of field effect transistors:

- **(*i*) Junction field effect transistor (*JFET*)**
- **(ii) Metal oxide semiconductor field effect transistor (*MOSFET*)**

To begin with, we shall study about *JFET* and then improved form of *JFET*, namely; *MOSFET.*

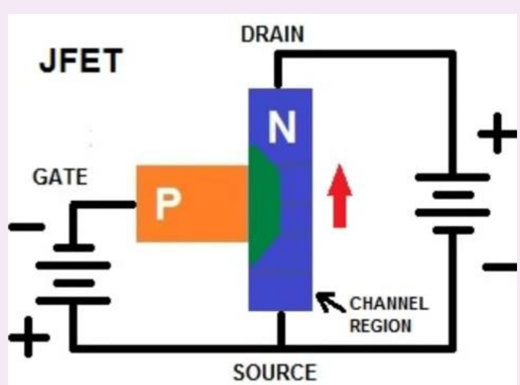


Junction Field Effect Transistor (JFET)

A **junction field effect transistor** *is a three terminal semiconductor device in which current conduction is by one type of carrier i.e., electrons or holes.*

The *JFET* was developed about the same time as the transistor but it came into general use only in the late 1960s. In a *JFET*, the current conduction is either by electrons or holes and is controlled by means of an electric field between the gate electrode and the conducting channel of the device.

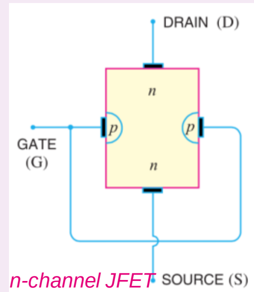
The *JFET* has high input impedance and low noise level.



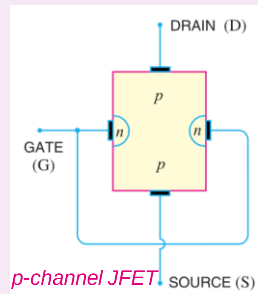
Construction of JFET

A *JFET* consists of a *p*-type or *n*-type silicon bar containing two *pn* junctions at the sides as shown. The bar forms the conducting channel for the charge carriers.

The two *pn* junctions forming diodes are connected internally and a common terminal called *gate* is taken out. Other terminals are *source* and *drain* taken out from the bar as shown. Thus a *JFET* has essentially three terminals *viz*., *gate* (*G*), *source* (*S*) and *drain* (*D*).



n-channel JFET



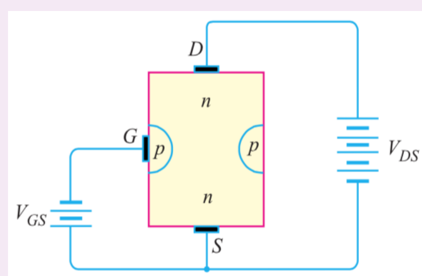
p-channel JFET

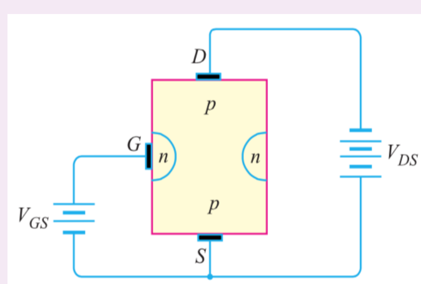
JFET polarities

The voltage between the gate and source is such that the gate is reverse biased.

The following points may be noted:

- ***(i)*** The input circuit (*i.e.* gate to source) of a *JFET* is reverse biased. This means that the device has high input impedance.
- ***(ii)*** The drain is so biased w.r.t. source that drain current I_D flows from the source to drain.
- ***(iii)*** In all *JFETs*, source current I_S is equal to the drain current *i.e.* $\mathbf{I_S = I_D}$.





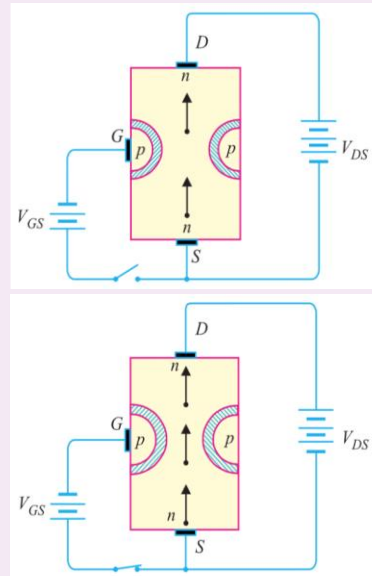
Principle and Working of JFET

The two *pn* junctions at the sides form two depletion layers. The current conduction by charge carriers (*i.e.* free electrons) is through the channel between the two depletion layers and out of the drain.

The width (resistance) of this channel can be controlled by changing the input voltage V_{GS}.

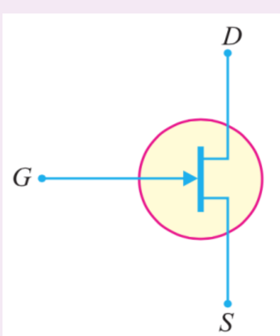
The greater the reverse voltage V_{GS}, the wider will be the depletion layers and narrower will be the conducting channel.

Thus JFET operates on the principle that width and hence resistance of the conducting channel can be varied by changing the reverse voltage V_{GS}. In other words, the magnitude of drain current (I_D) can be changed by altering V_{GS}.

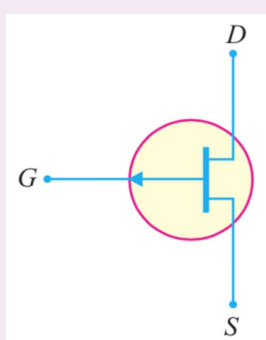


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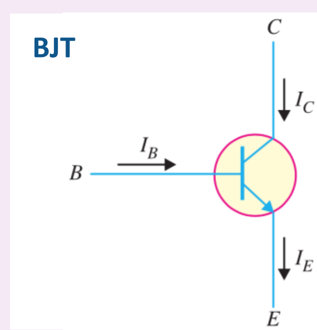
Symbol of JFET

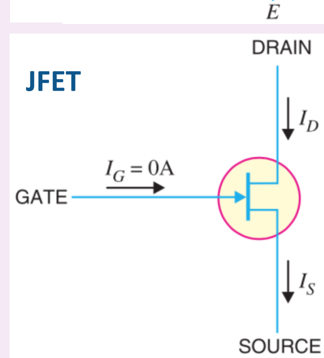


N Channel JFET



P Channel JFET





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JFET as an Amplifier

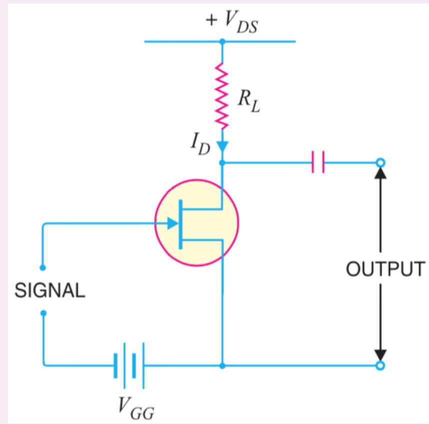
The weak signal is applied between gate and source and amplified output is obtained in the drain-source circuit. For the proper operation of *JFET*, input circuit should always be reverse biased by inserting a battery V_{GG} in the gate circuit.

A small change in the reverse bias on the gate produces a large change in drain current.

During the positive half of signal, the reverse bias on the gate decreases. This increases the channel width and hence the drain current.

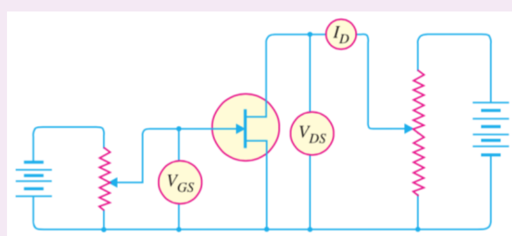
During the negative half-cycle of the signal, the reverse voltage on the gate increases. Consequently, the drain current decreases.

The result is that a small change in voltage at the gate produces a large change in drain current. These large variations in drain current produce large output across the load R_L. In this way, *JFET* acts as an amplifier.



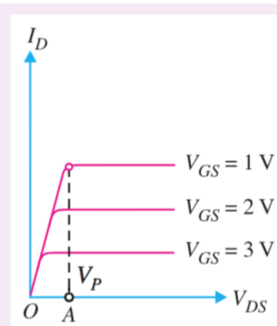
Output Characteristics of JFET

The curve between drain current (I_D) and drain-source voltage (V_{DS}) of a *JFET* at constant gate-source voltage (V_{GS}) is known as *output characteristics of JFET*.



(i) At first, the drain current I_D rises rapidly with drain-source voltage V_{DS} but then becomes constant. The drain-source voltage above which drain current becomes constant is known as *pinch off voltage*.

(ii) After pinch off voltage, the channel width becomes so narrow that depletion layers almost touch each other. The drain current passes through the small passage between these layers. Therefore, increase in drain current is very small with V_{DS} above pinch off voltage. Consequently, drain current remains constant.

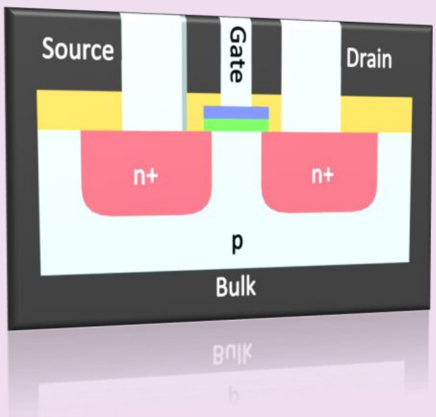


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Unit 6: Field Effect Transistor (FET)

Lecture 20: Metal Oxide Semiconductor FET (MOSFET)

Dr. Hazem Falah Sakeek

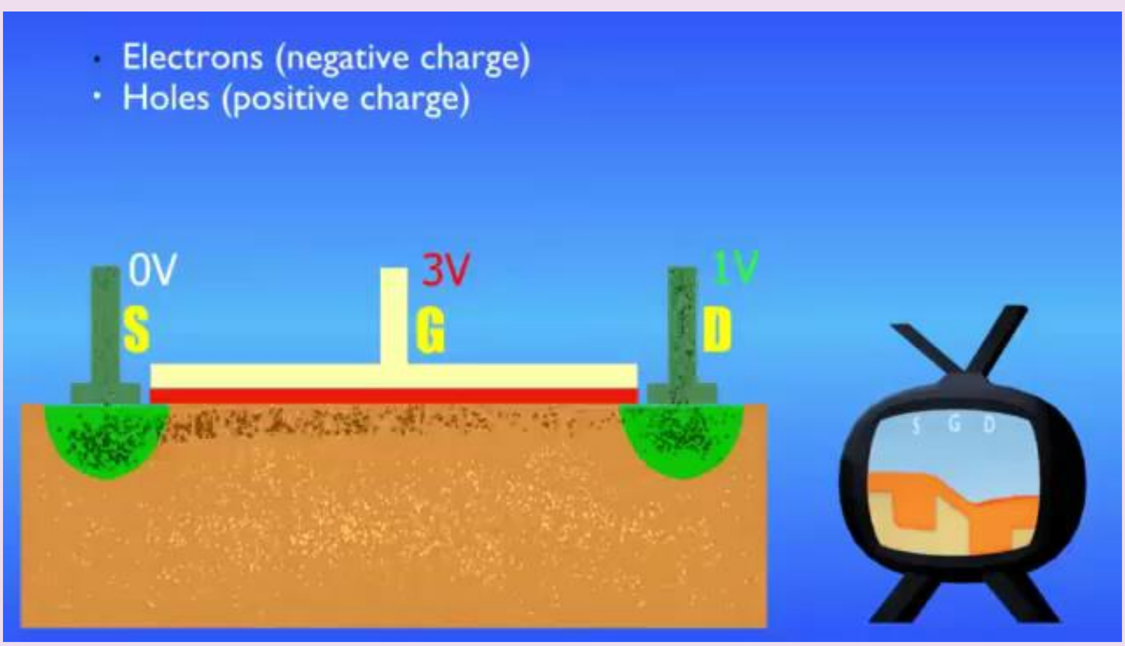
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Introduction

- The **MOSFET** (**m**etal **o**xide **s**emiconductor **f**ield-**e**ffect **t**ransistor) is another category of field-effect transistor. The MOSFET, different from the JFET, has no *pn* junction structure; instead, the gate of the MOSFET is insulated from the channel by a silicon dioxide (SiO_2) layer.
- A *MOSFET* is an important semiconductor device and can be used in any of the circuits covered for *JFET*. However, a *MOSFET* has several advantages over *JFET* including high input impedance and low cost of production.

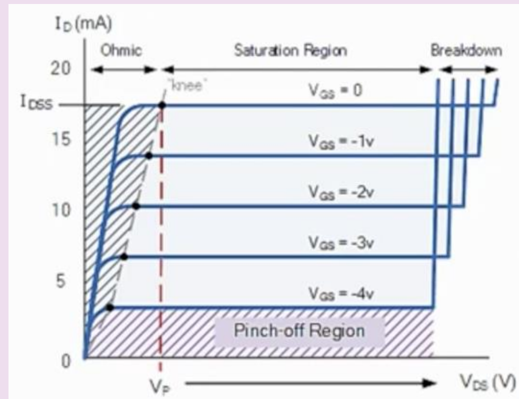
Dr. Hazem Falah Sakeek | www.hazemsakeek.net | www.physicsacademy.org

- Transistor Family
  - Field Effect Transistor (FET)
    - Junction FET
      - Depletion mode
        - N channel
        - P channel
    - Metal Oxide Semiconductor FET
      - Depletion mode
        - N channel
        - P channel
      - Enhancement mode
        - N channel
        - P channel
  - Bipolar Junction Transistor (BJT)
    - NPN
    - PNP



Drawback of *JFET*

- The main drawback of *JFET* is that its gate *must* be reverse biased *i.e.* it can only have negative gate operation for *n*-channel and positive gate operation for *p*-channel.
- This means that we can *only* decrease the width of the channel from its zero-bias size.
- This type of operation is referred to as *depletion-mode* operation. Therefore, a *JFET* can only be operated in the depletion-mode.



A field effect transistor (FET) that can be operated in the enhancement-mode is called a MOSFET.

Types of MOSFETs

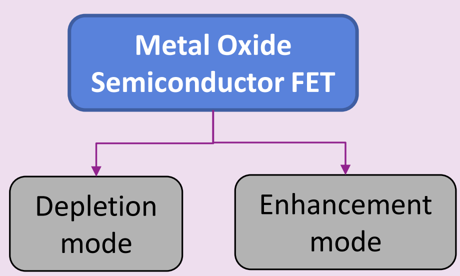
There are two basic types of *MOSFETs viz.*

1. Depletion-type *MOSFET* or ***D-MOSFET.***

The *D-MOSFET* can be operated in both the depletion-mode and the enhancement-mode. For this reason, a *D-MOSFET* is sometimes called depletion/enhancement *MOSFET*.

2. Enhancement-type *MOSFET* or ***E-MOSFET*.**

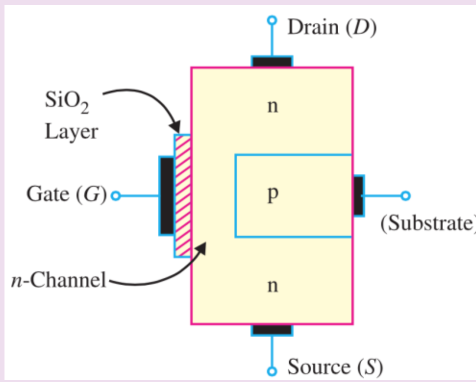
The *E-MOSFET* can be operated *only* in enhancement-mode.



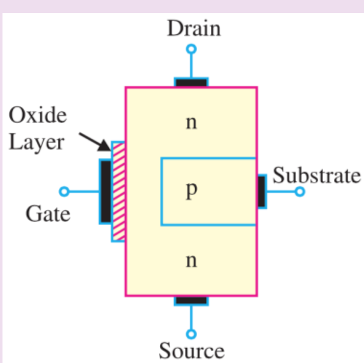
The manner in which a *MOSFET* is constructed determines whether it is *D-MOSFET* or *E- MOSFET*.

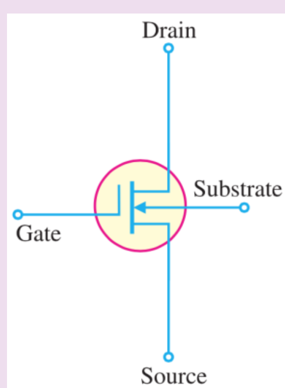
D-MOSFET

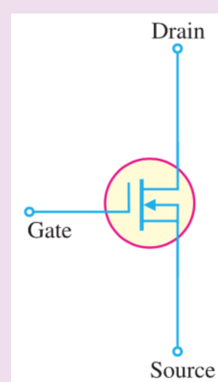
The *n*-channel *D-MOSFET* is a piece of *n*-type material with a *p*-type region (called *substrate*) on the right and an *insulated gate* on the left. The free electrons flowing from source to drain must pass through the narrow channel between the gate and the *p*-type region (*i.e.* substrate).



Symbols for D-MOSFET



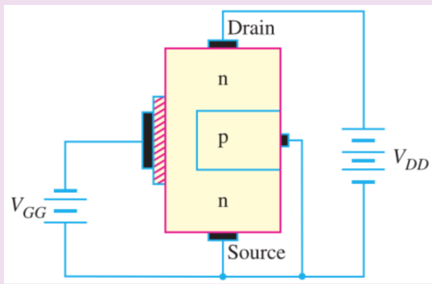


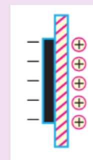


n-channel D-MOSFET

Circuit Operation of D-MOSFET

- The gate forms a small capacitor. One plate of this capacitor is the gate and the other plate is the channel with metal oxide layer as the dielectric.

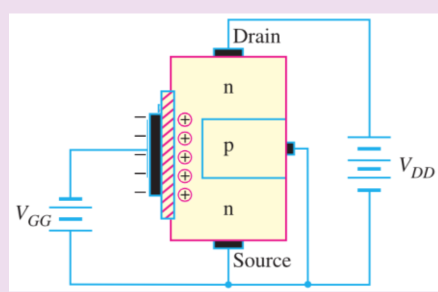




- When gate voltage is changed, the electric field of the capacitor changes which in turn changes the resistance of the n-channel.
- Since the gate is insulated from the channel, we can apply either negative or positive voltage to the gate. The negative-gate operation is called *depletion mode* whereas positive-gate operation is known as *enhancement mode.*

(1) Depletion mode

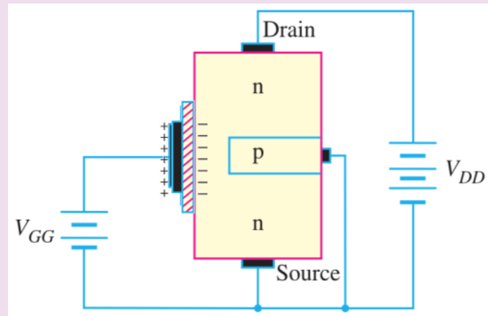
- The gate is negative.
- Electrons repel the free electrons in the *n*-channel, leaving a layer of positive ions in a part of the channel i.e. depleted the *n*-channel of some of its free electrons.
- Therefore the resistance of the channel is increased.
- By changing the negative voltage on the gate, we can vary the resistance of the *n*-channel and hence the current from source to drain.



Note: with negative voltage on the gate, the action of *D-MOSFET* is similar to *JFET*. Because the action with negative gate depends upon depleting the channel of free electrons, the negative-gate operation is called *depletion mode.*

(2) Enhancement mode

- The gate is positive.
- It induces negative charges in the *n*-channel.
- Because free electrons are added to those already in the channel, the total number of free electrons in the channel is increased.
- Thus a positive gate voltage *enhances* or *increases* the conductivity of the channel.
- By changing the positive voltage on the gate, we can change the conductivity of the channel.



Because the action with a positive gate depends upon *enhancing* the conductivity of the channel, the positive gate operation is called *enhancement mode.*

Some Remarks

(1) In a *D-MOSFET*, the source to drain current is controlled by the electric field of capacitor formed at the gate.

(2) The gate of *JFET* behaves as a reverse-biased diode whereas the gate of a *D-MOSFET* acts like a capacitor. For this reason, it is possible to operate *D-MOSFET* with positive or negative gate voltage.

(3) As the gate of *D-MOSFET* forms a capacitor, therefore, negligible gate current flows whether positive or negative voltage is applied to the gate. For this reason, the input impedance of *D-MOSFET* is very high, ranging from 10,000 MΩ to 1,000,000 MΩ.

(4) The extremely small dimensions of the oxide layer under the gate terminal result in a very low capacitance and the *D-MOSFET* has, therefore, a very low input capacitance. This characteristic makes the *D-MOSFET* useful in high-frequency applications.

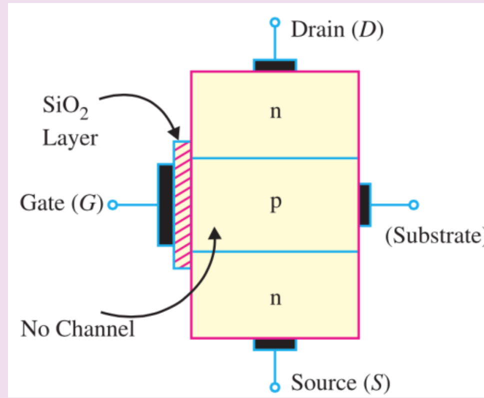
E-MOSFET

The *E-MOSFET* has no channel between source and drain unlike the *D-MOSFET*.

The substrate extends completely to the SiO_2 layer so that no channel exists.

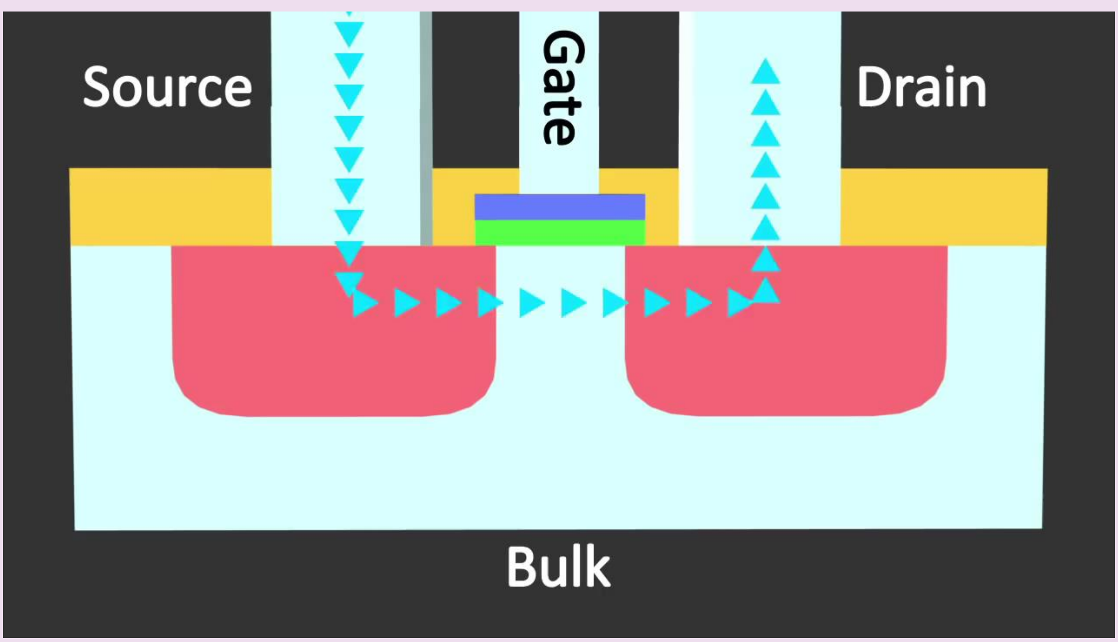
The *E-MOSFET* requires a proper gate voltage to *form* a channel (called induced channel).

It is reminded that *E-MOSFET* can be operated *only* in enhancement mode.

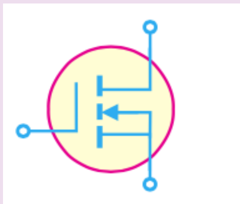


In short, the construction of *E-MOSFET* is quite similar to that of the *D-MOSFET* except for the absence of a channel between the drain and source terminals.

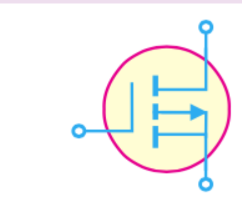
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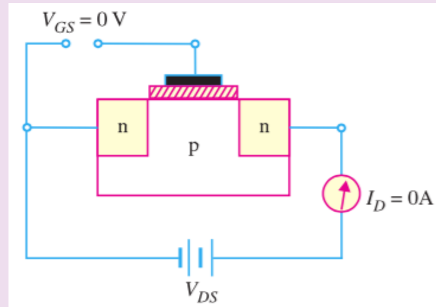
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***n*-channel**
E-MOSFET



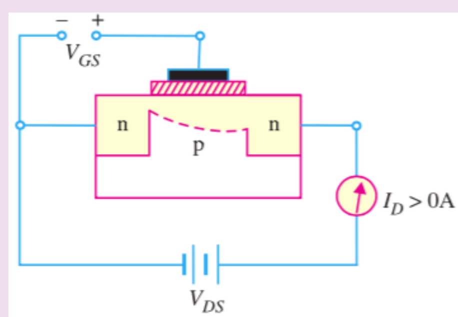
***p*-channel**
E-MOSFET



- When V_{GS} = 0V, there is no channel connecting the source and drain.
- For this reason, *E-MOSFET* is normally *OFF* when V_{GS} = 0 V.

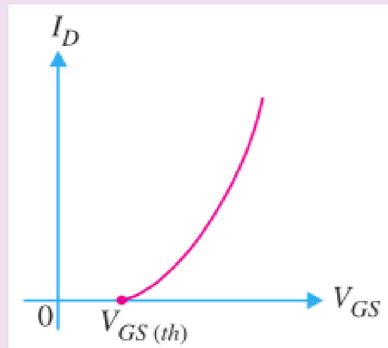
Note that this behavior of *E-MOSFET* is quite different from *JFET* or *D-MOSFET.*

- When gate is made positive, it attracts free electrons into the *p* region.
- The free electrons combine with the holes next to the SiO_2 layer.
- If V_{GS} is positive enough, all the holes touching the SiO_2 layer are filled and free electrons begin to flow from the source to drain.



The minimum value of V_{GS} that turns the E-MOSFET ON is called ***threshold voltage*** [$V_{GS\,(th)}$].

- When V_{GS} is less than $V_{GS\ (th)}$, there is no induced channel and the drain current I_D is zero.
- When V_{GS} is equal to $V_{GS\ (th)}$, the *E-MOSFET* is turned *ON* and the induced channel conducts drain current from the source to the drain.
- Beyond $V_{GS\ (th)}$, if the value of V_{GS} is *increased*, the newly formed channel becomes wider, causing I_D to increase.



The end

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أستاذ الفيزياء المشارك
جامعة الأزهر - غزة



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- مؤسس وعميد كلية الدراسات المتوسطة بجامعة الازهر - غزة من الفترة ١٩٩٦-٢٠٠٥
- عميد القبول والتسجيل بجامعة الازهر - غزة في الفترتين ١٩٩٨-٢٠٠٠ و٢٠٠٧-٢٠٠٨
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